



Ministry  
of Defence



SHEFFIELD FORGEMASTERS

# Advancing Nuclear Component Manufacturing: Harnessing Local Vacuum Electron Beam Welding

by

Jesus Talamantes-Silva

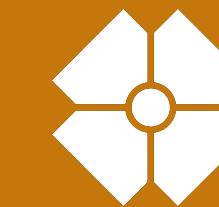
Research, Design and Technology Director

24 October 2023



Department for  
Energy Security  
& Net Zero

Project Leads at SFEL: M Blackmore and J Pope  
Special Thanks: S Falder, J Khalifa and C Punshon



## Agenda

1. Company Background
2. Advanced Manufacturing
3. Electron Beam Welding
4. Conclusions and Future work

**01**

BACKGROUND



## Capabilities and Markets

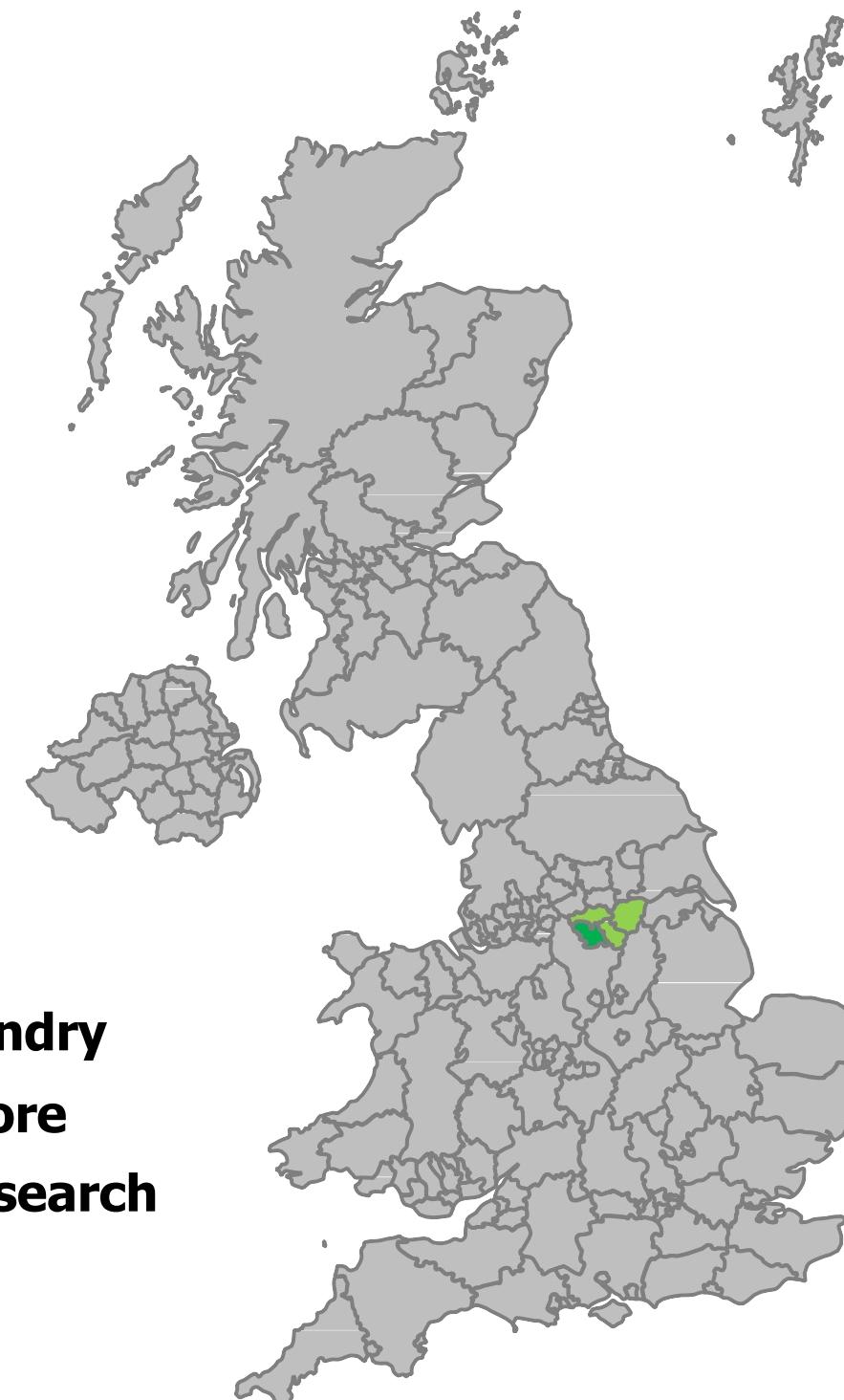
### **Sheffield, UK**

**610**  
**Staff**

**One-stop shop for design,  
manufacture, inspection  
and testing.**

**Capability**

**Steelmaking, forging, foundry  
casting, machining, offshore  
design & manufacture, research  
and development, sales.**



- Defence
- Nuclear
- Offshore
- Steel Processing
- Steel Plant
- Pressure Vessels

## Capabilities and Markets



**CASTINGS**

- c650T casting weight
- Pattern and mould making
- c350T finish weight

**RECAPITALISATION PROGRAM**

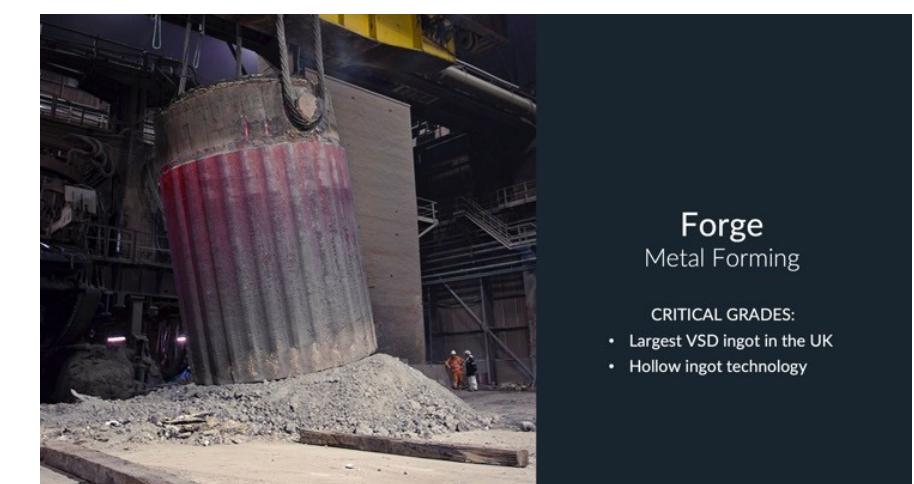
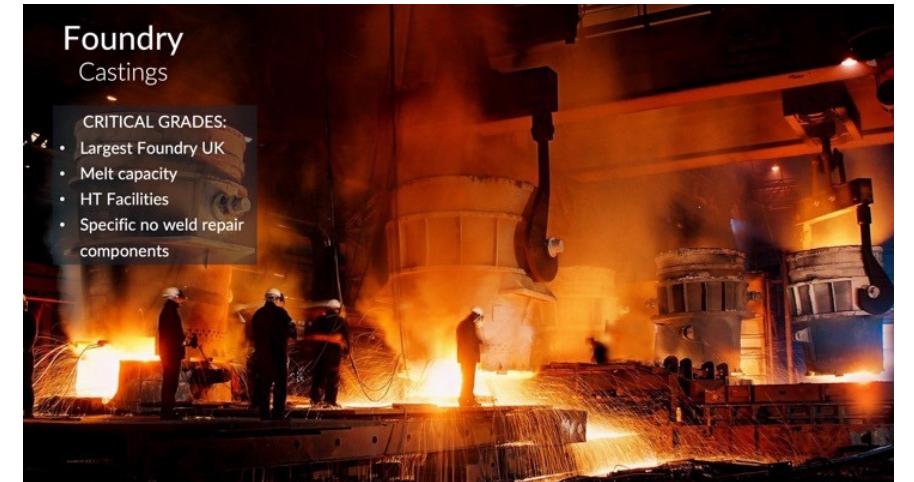
- Investment program
- State of the art machine shop
- New forging line

**FORGINGS**

- 285T Ingot
- 10,000T and 4,500T Press
- c5m diameter discs/hollows
- c20m max length

**KEY CHALLENGES**

- Business Interruption
- Competing market sectors
- Market uncertainty
- Energy/Raw materials security
- Capacity requirements



**02**

**ADVANCED  
MANUFACTURING**



## Added value activities

### Innovation and Technology

- Advanced Manufacturing
  - **Electron Beam Welding**
  - Cladding
  - NDT
  - Cast and HIP
  - Automation and I4.0
- Design for manufacture
- Plant and process development
- ICME: Integrated Computational Materials Engineering
- Net-zero carbon technologies
- High temperature materials (RA steels)

### Benefits

- *Developing unique products*
- *Provides competitive advantage*
- *Provides long term income*
- *Identifies new opportunities*
- *Improves efficiency*
- *Enhances reputation*

### Challenges

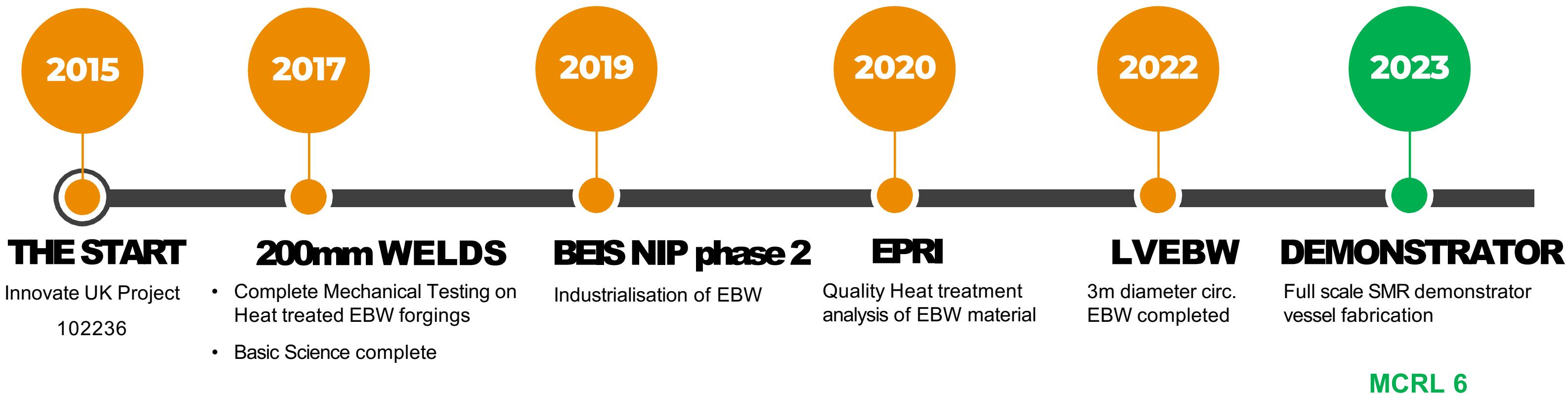
- *High financial costs*
- *Long timescales*
- *Uncertain outcomes*
- *Conditions may change*
- *Reactions of rival companies*
- *Possibility of failure*

**03**

ELECTRON  
BEAM WELDING

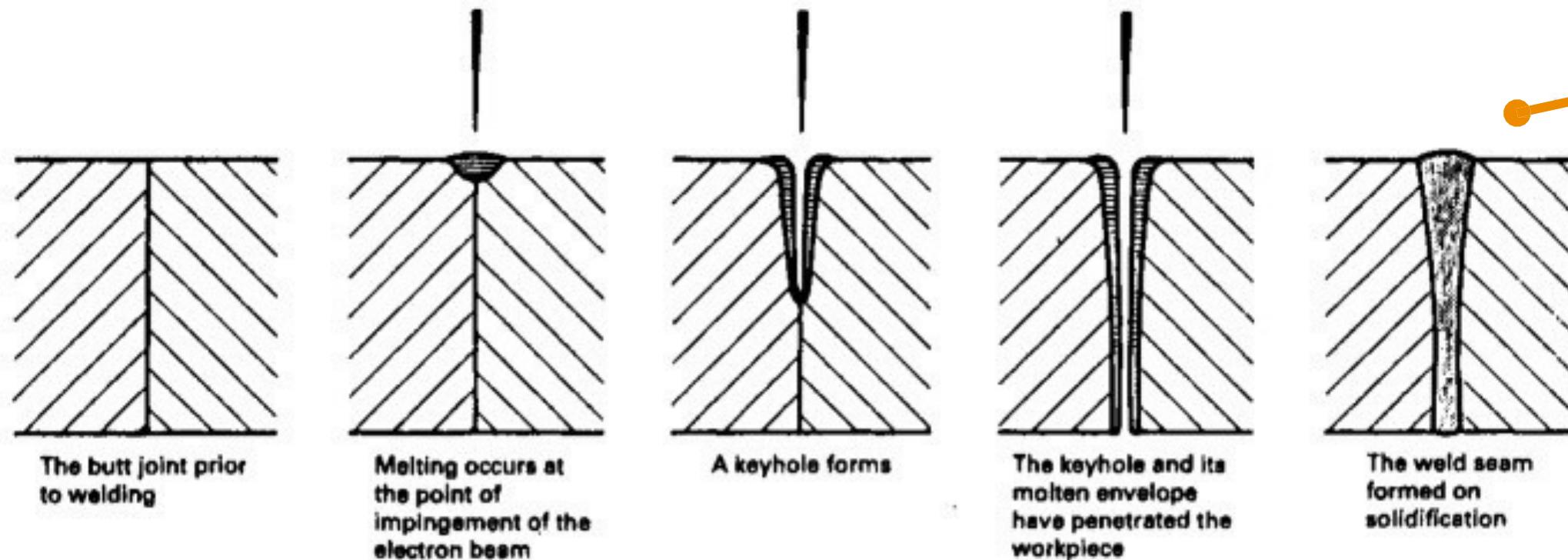


## Advanced Manufacturing

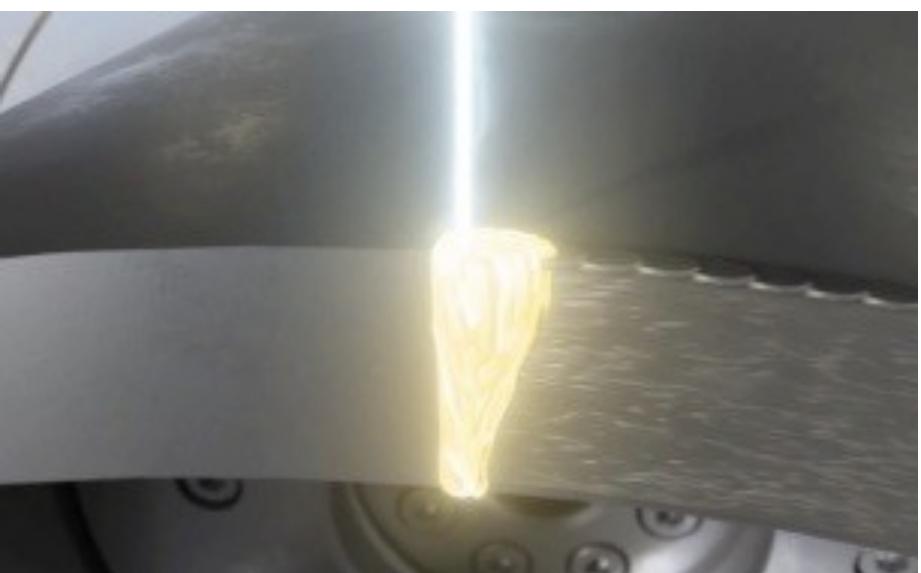
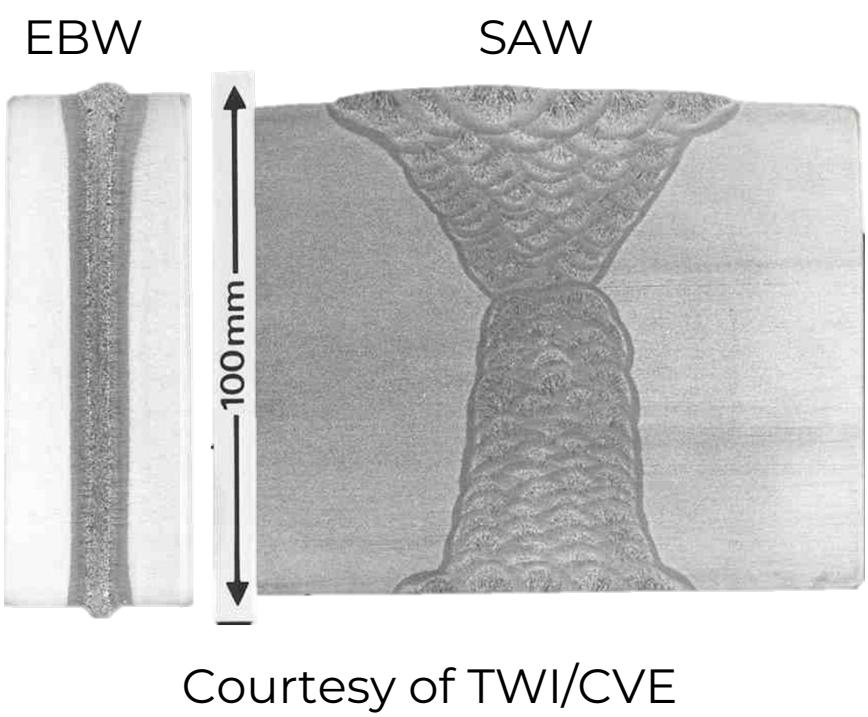


Electron Beam Welding is a key advanced manufacturing capability to enable Sheffield Forgemasters to support SMR and AMR commercialisation through added value activities.

## Electron Beam Welding



Stages of EBW penetration taken from  
Electron beam welding by H Schultz, 2004

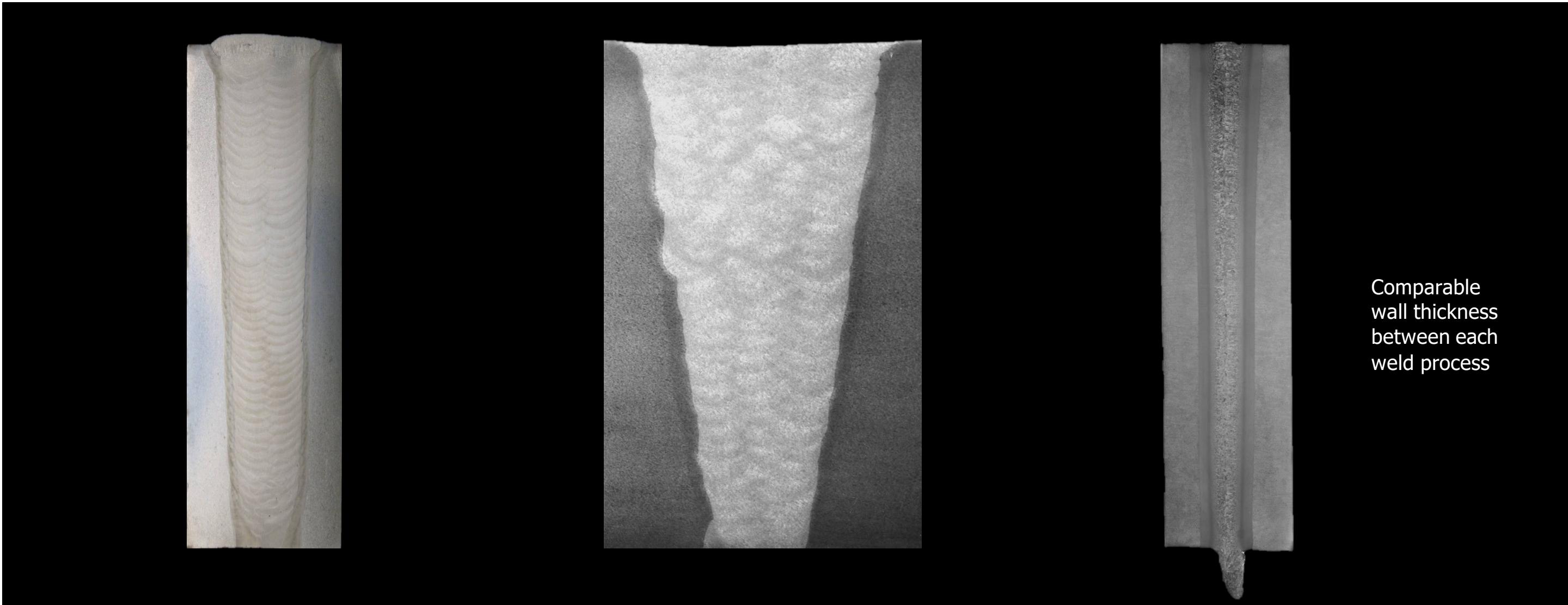


Courtesy of CVE

2015

2017

## Electron Beam Welding



2015

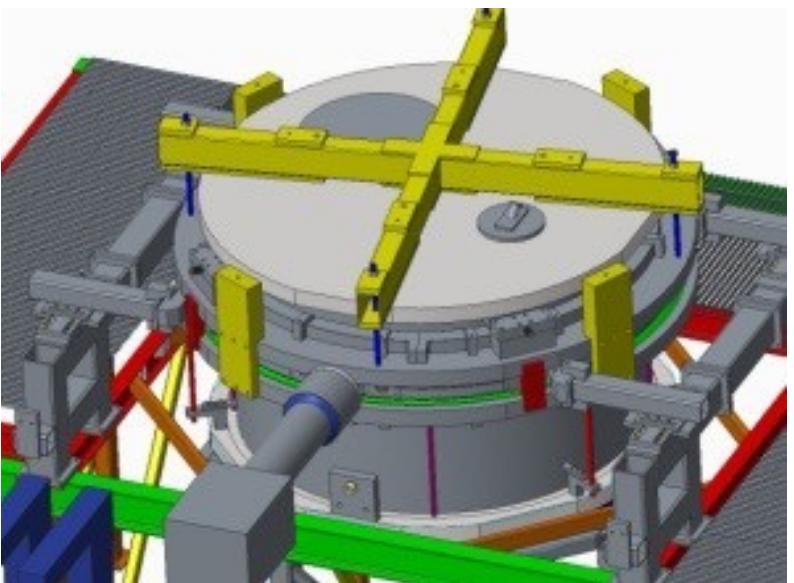
**A) Narrow Gap Tungsten Inert Gas (NG-TIG)**  
**Circa 90 passes**  
**MONTHS**

**B) Submerged Arc Welding (SAW)**  
**Circa 70 passes**  
**WEEKS**

**C) Electron Beam Welding (EBW)**  
**Single pass**  
**HOURS**

2017

Operation in reduced vacuum (Pressure 1 to 0.01mBar)



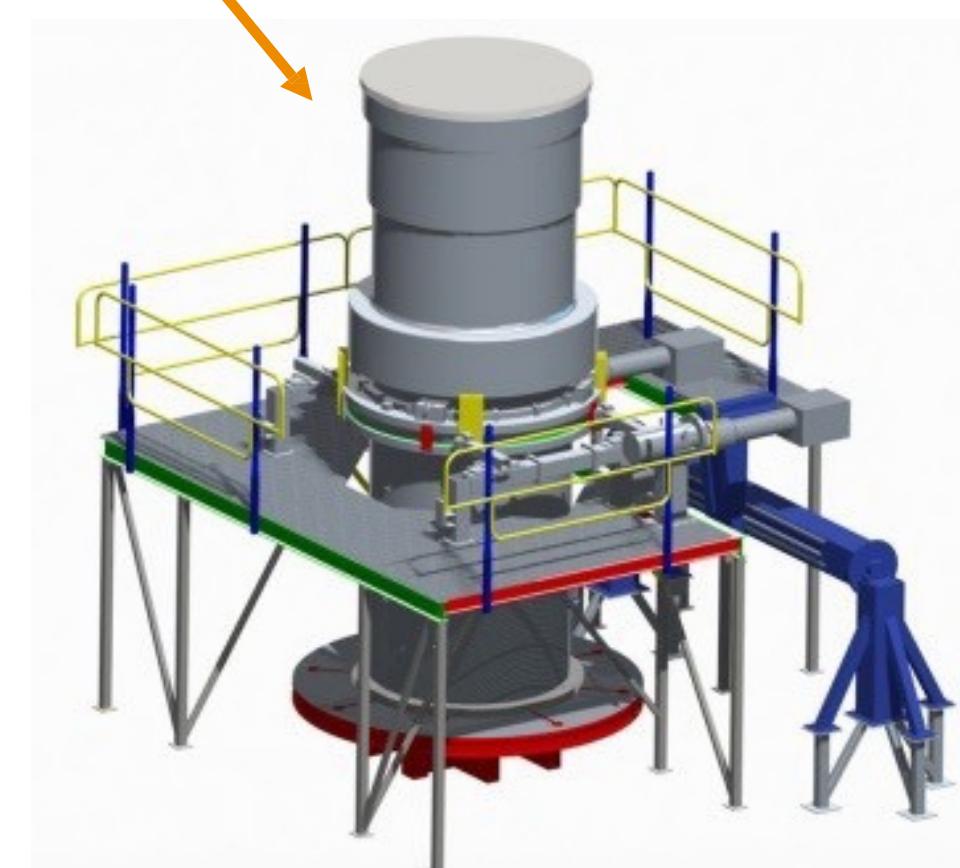
**Development**



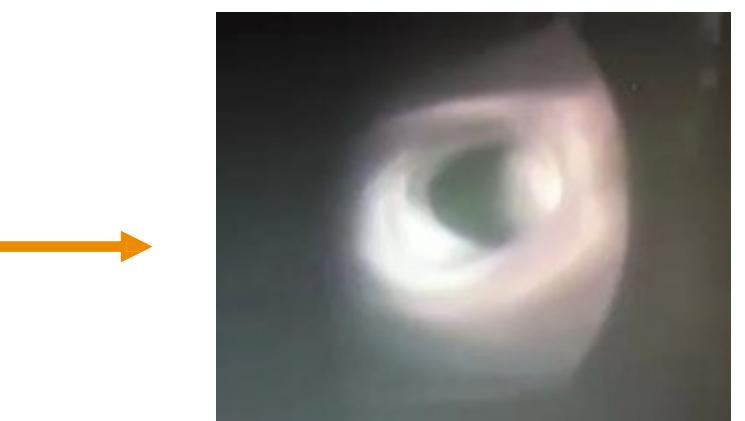
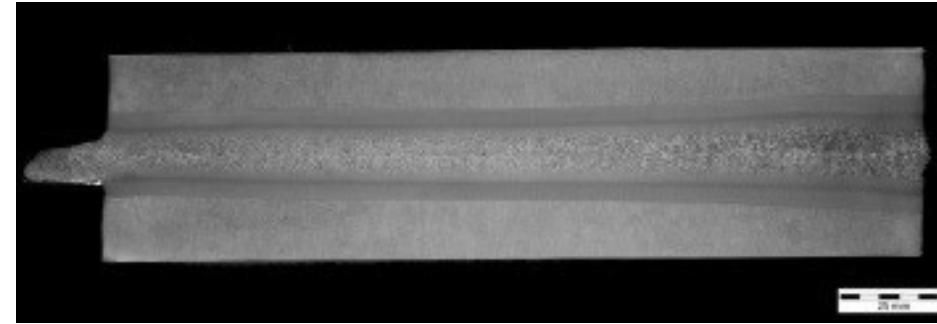
**Implementation**

2015

**Final fabrication assembly weld.**



**Stable keyhole using key  
welding parameters for SA508**



2017

## Heat Treatment



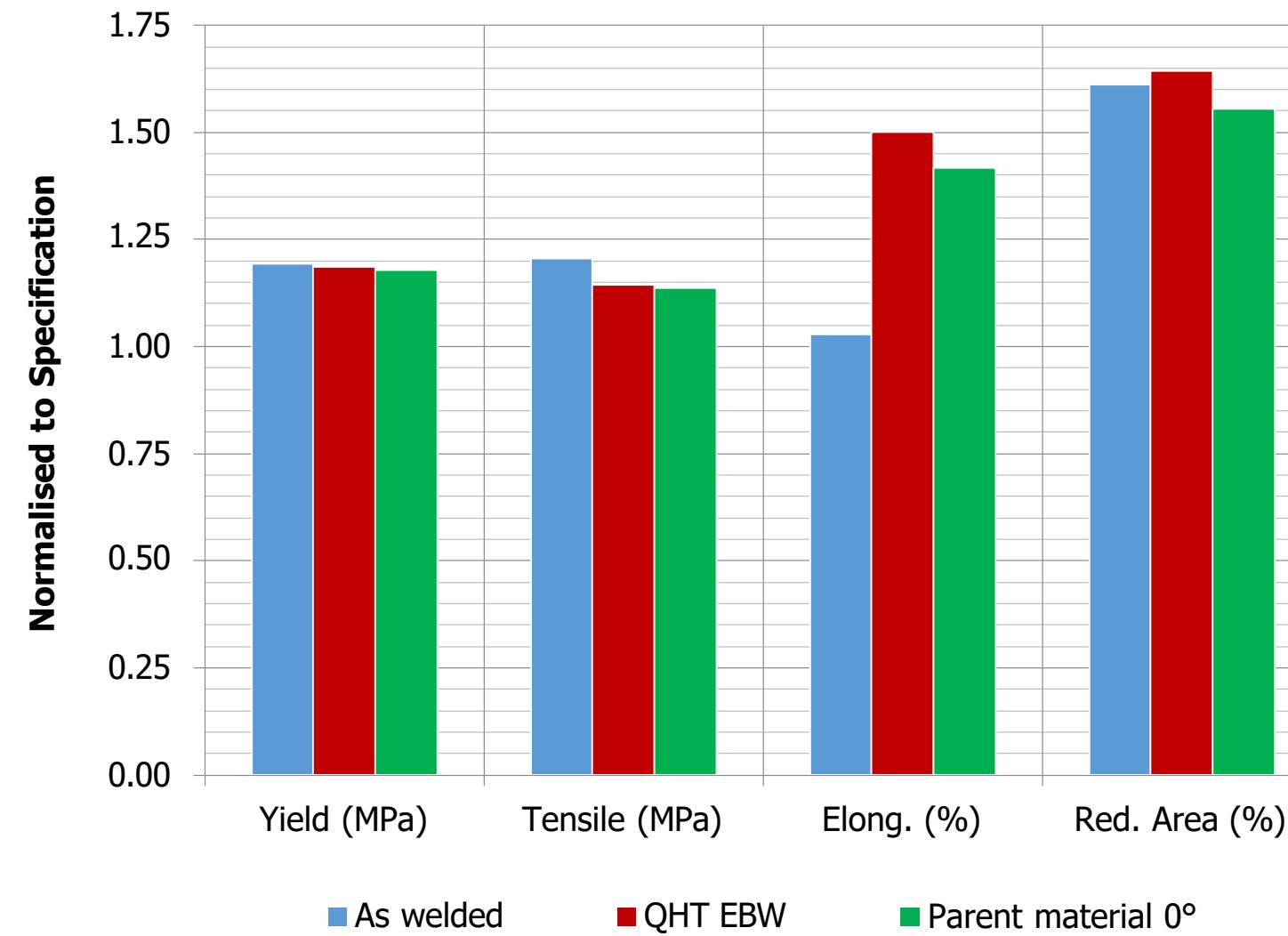
2015

**Quality heat treatment**

2017

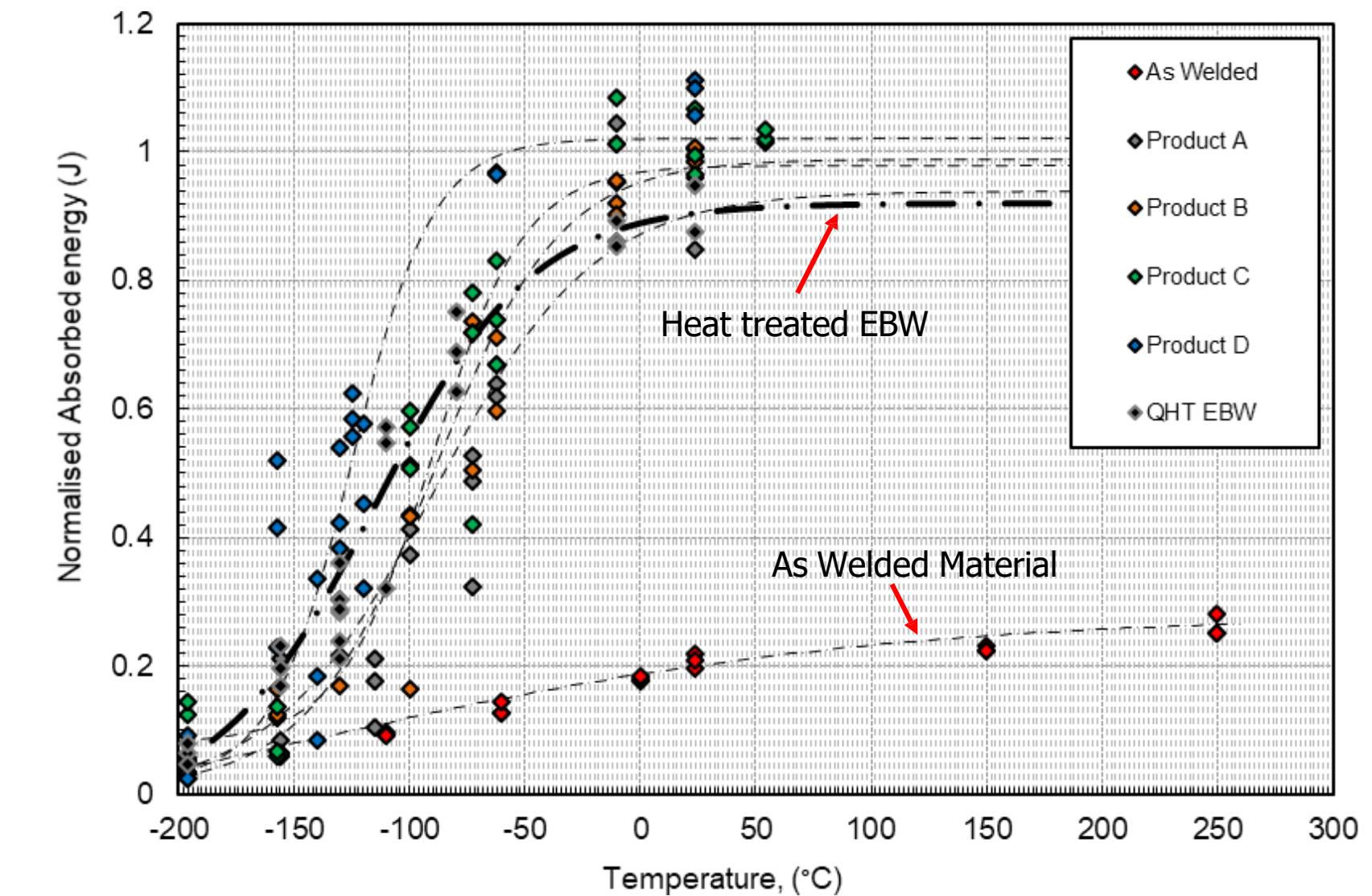
**Mechanical testing extraction**

## Mechanical Properties



**Selected Mechanical Properties**

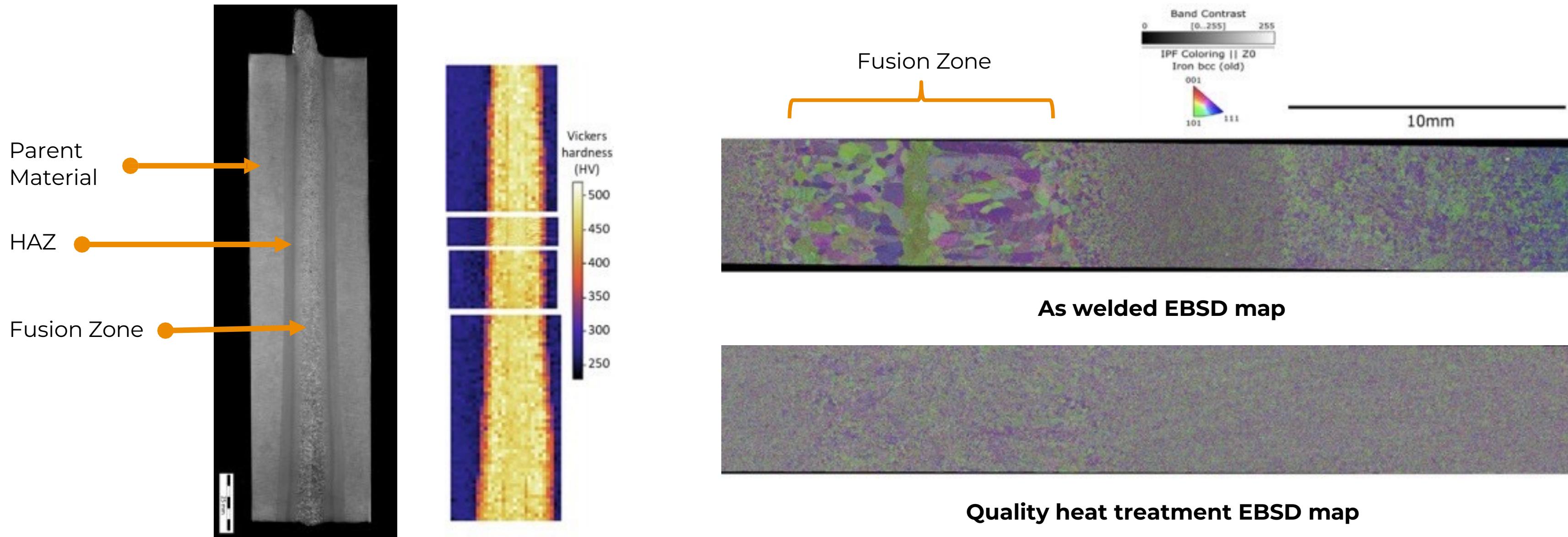
2015



**Charpy Impact FATT**

2017

## Weld Characterisation



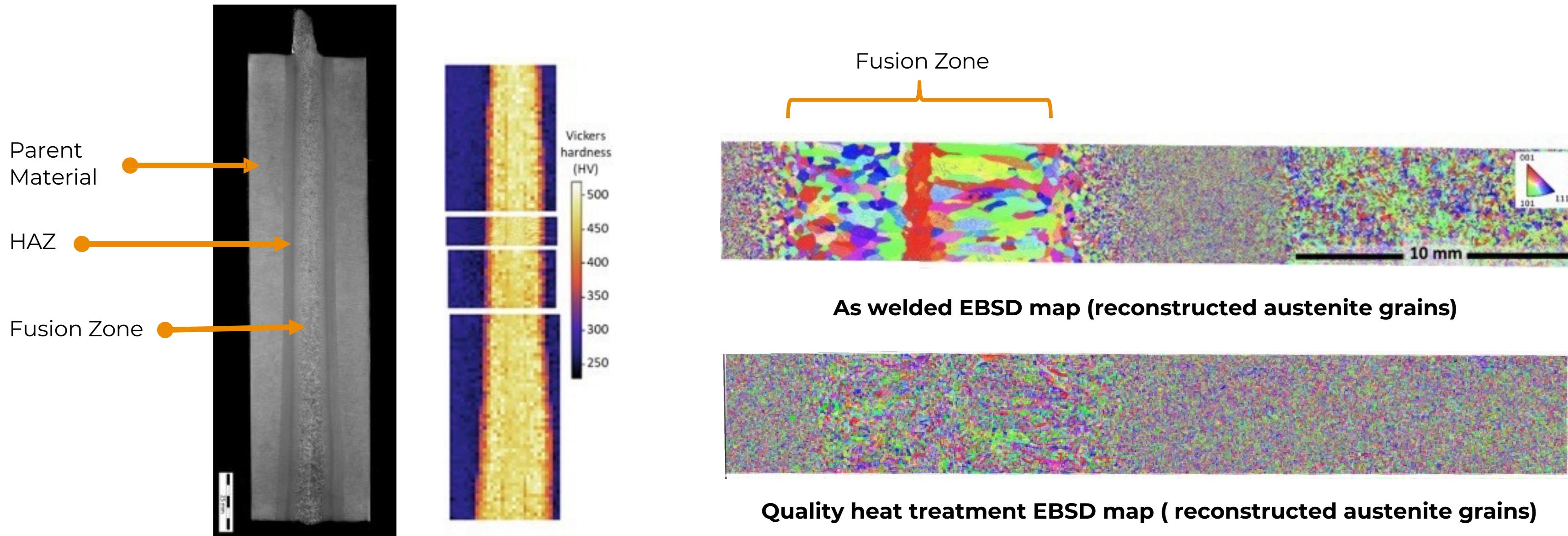
2015

**SA508 Type Material  
welded at SFEL**

2017

Weld Characterised at UoM, K Bruce and E Pickering.

## Weld Characterisation



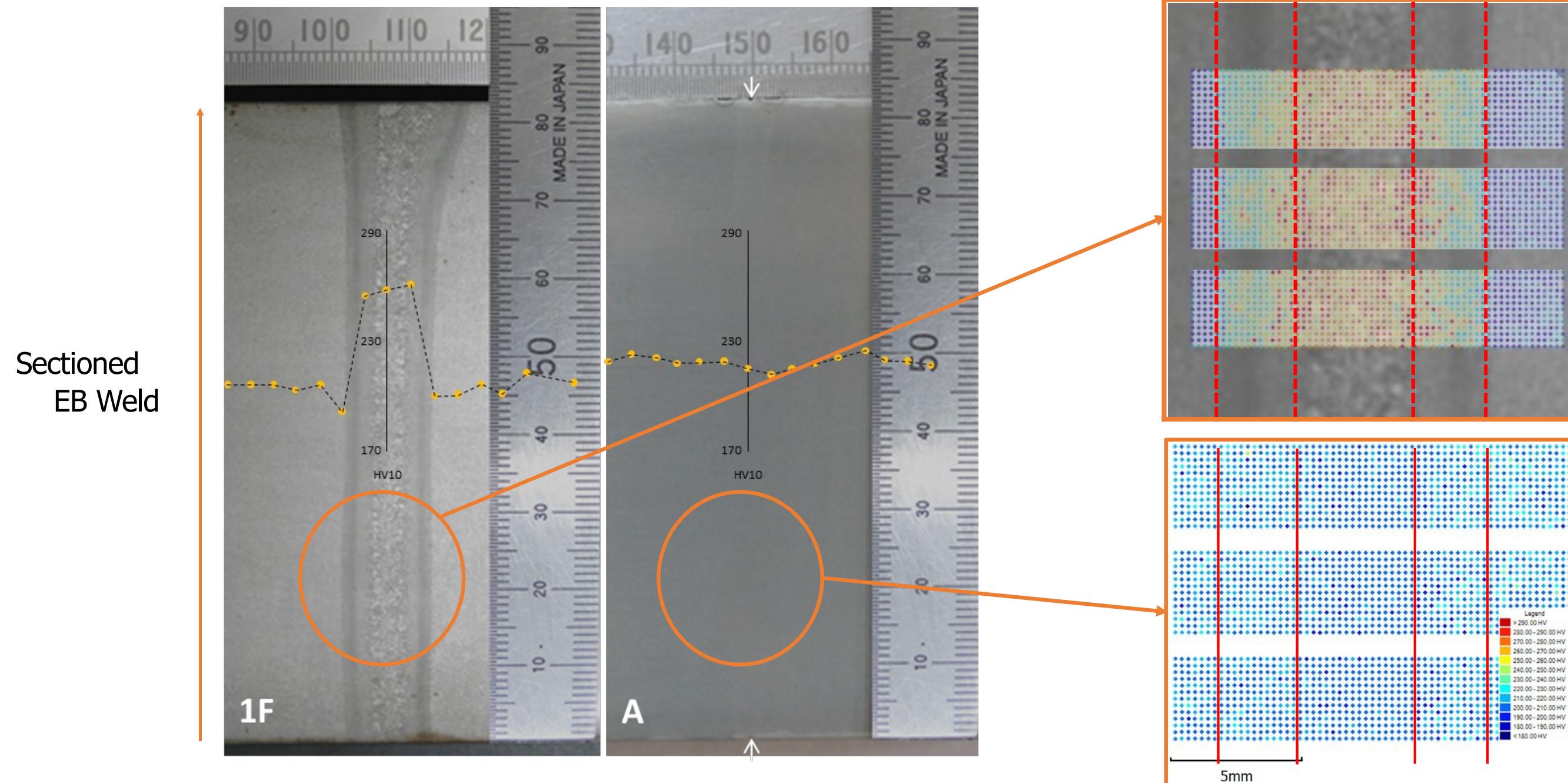
2015

**SA508 Type Material  
welded at SFEL**

2017

Weld Characterised at UoM, K Bruce and E Pickering.

## Electron Beam Welding Quality: Hardness map



Reference: Program on Technology Innovation: Small Modular Reactor Vessel Manufacture and Fabrication, D Gandy and M Albert, 2021

## Industrialisation

Technology Readiness Levels (TRL)	EBW Current Status
<ul style="list-style-type: none"><li>• TRL 1 Bright idea</li><li>• TRL 2–3 Scientific investigation</li><li>• TRL 4 Laboratory scale testing</li><li>• TRL 5 Large scale rig testing</li><li>• TRL 6 Full scale system demonstration</li><li>• TRL 7 Service test</li><li>• TRL 8 Product development and prototyping</li><li>• TRL 9 Mature product in service</li></ul>	<ul style="list-style-type: none"><li>✓ Done for years</li><li>✓ Done for years</li><li>✓ TWI/AxRC environment test blocks</li><li>✓ Innovate 102236 Project</li><li>✗ BEIS NIP Phase 2 <a href="#">demonstration</a></li><li>✗ Find vendor</li><li>✗ Test in reactor</li><li>✗ Entry into service</li></ul>

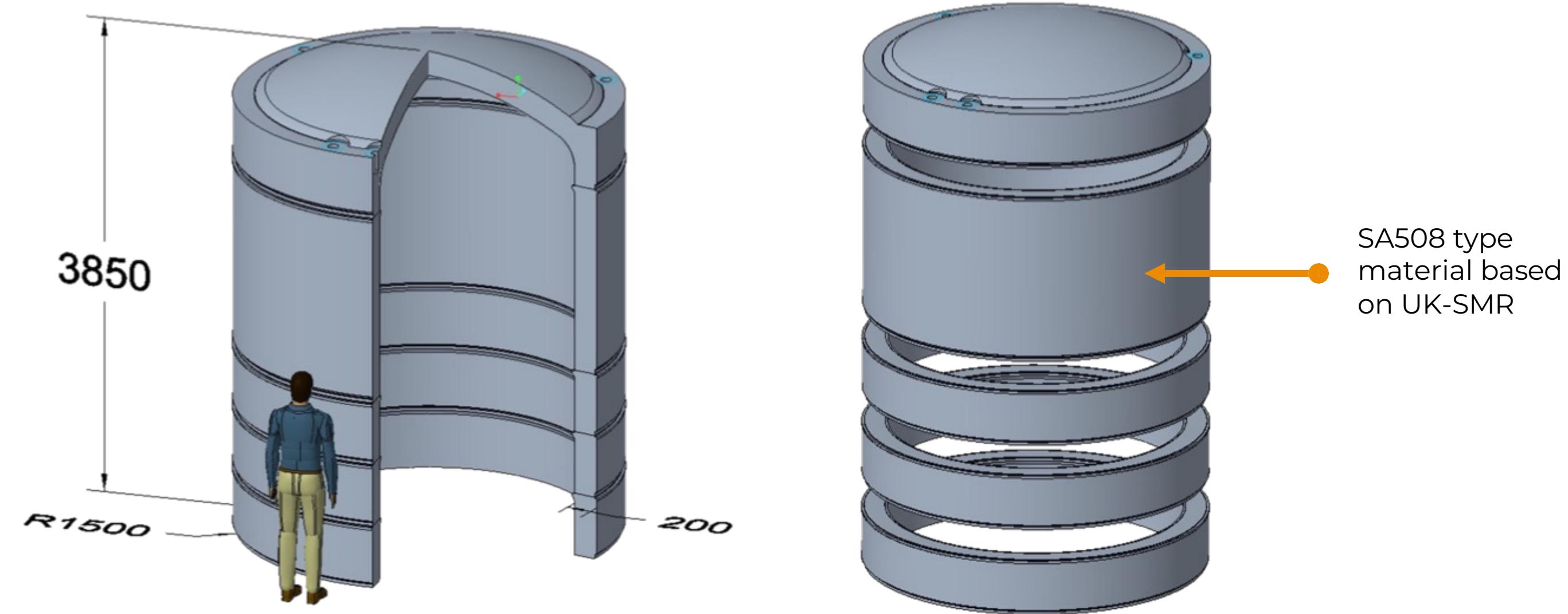
Manufacturing Capability Readiness Levels (MCRL)	EBW Current Status
<ul style="list-style-type: none"><li>• MCRL 1 - 4 Conception and assessment of the technology.</li><li>• MCRL 5 - 6 Pre-production phase, full-scale equipment and processes</li><li>• MCRL 7 - 9 Implementation on the shop floor, volume production</li></ul>	<ul style="list-style-type: none"><li>✓ Innovate 102236 Project</li><li>✗ BEIS NIP Phase 2 <a href="#">demonstration</a></li><li>✗ SFIL Production Facility</li></ul>

2019

With support from the Department for Business, Energy & Industrial Strategy  
(now the Department for Energy Security and Net Zero: DESNZ)

2023

## Full-scale system demonstration



2019

With support from the Department for Business, Energy & Industrial Strategy  
(now the Department for Energy Security and Net Zero: DESNZ)

2023



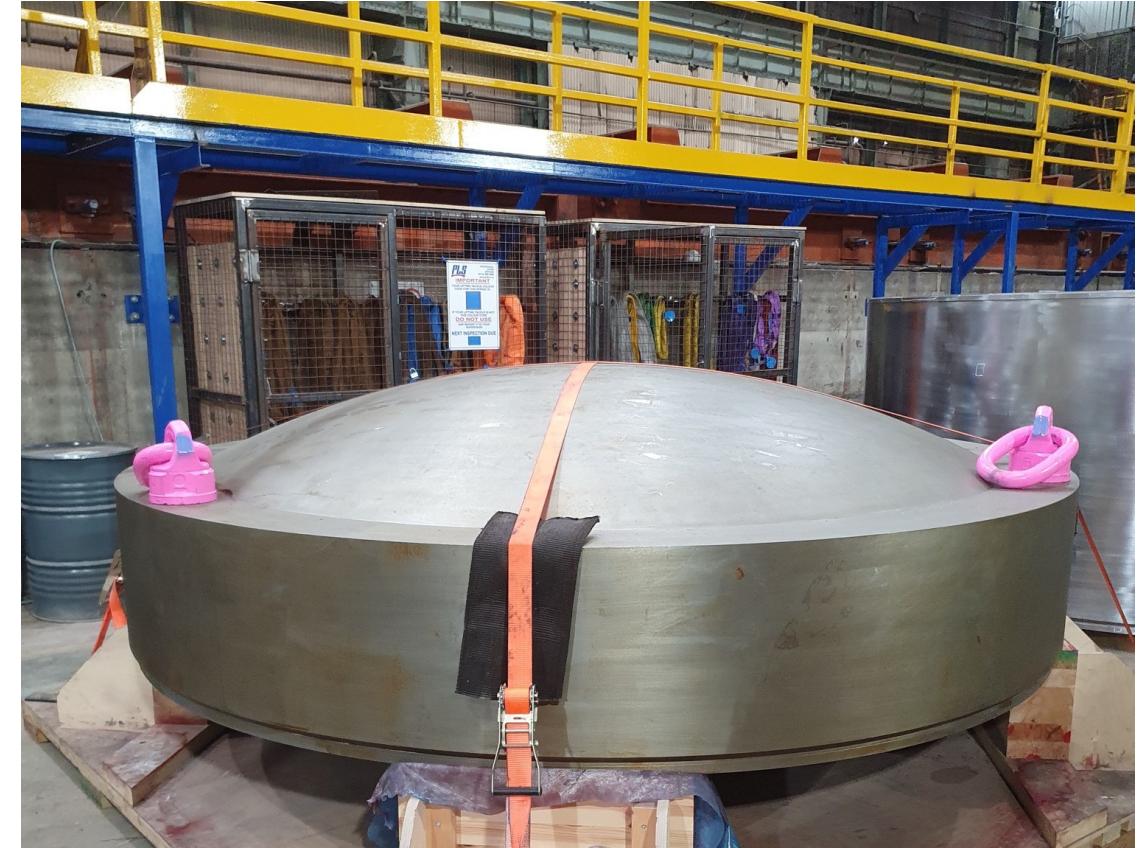
**Ring Forgings**

2019



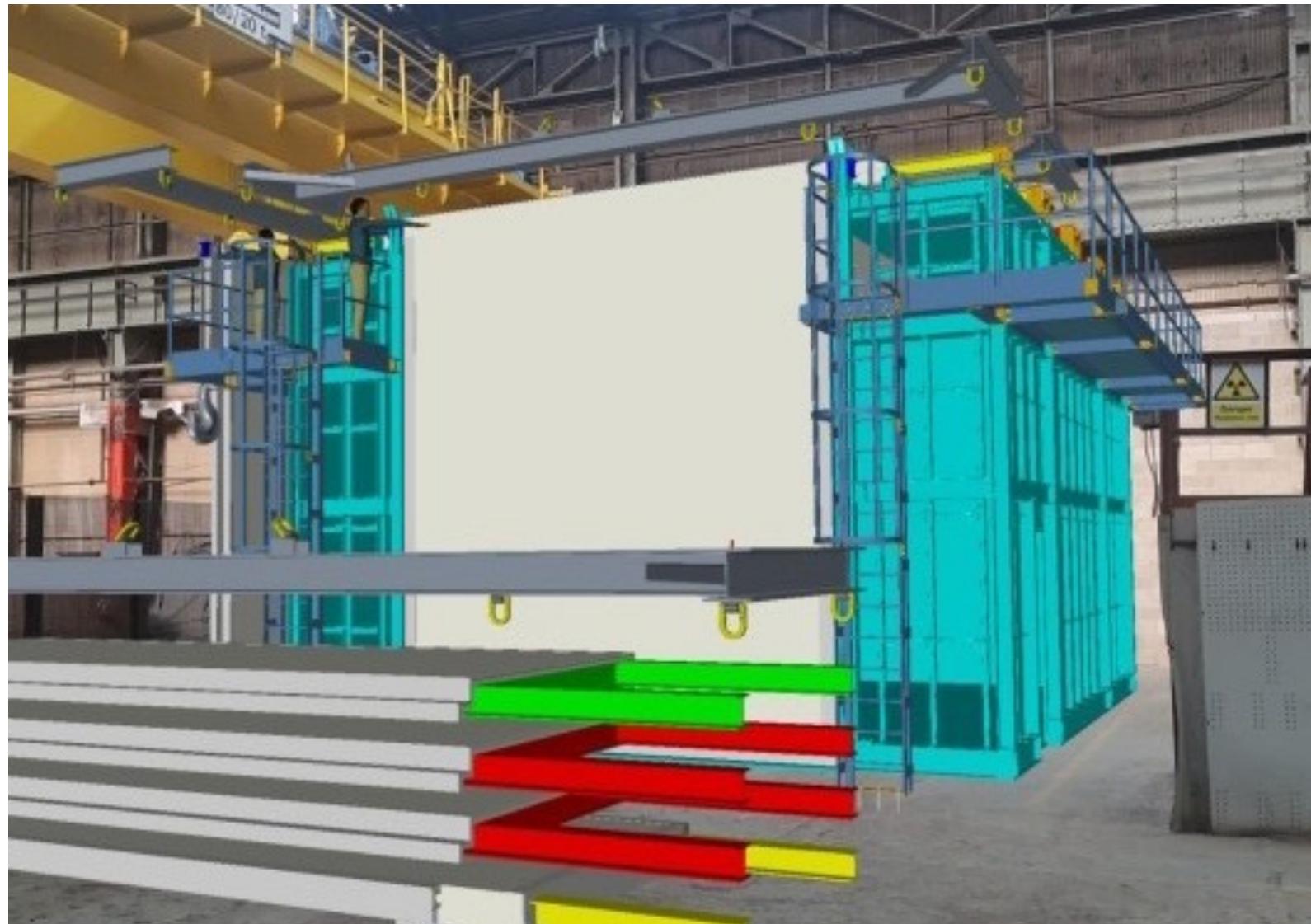
**Shell Forging**

2023



**Head Forging**

## Large scale EB facility



2019

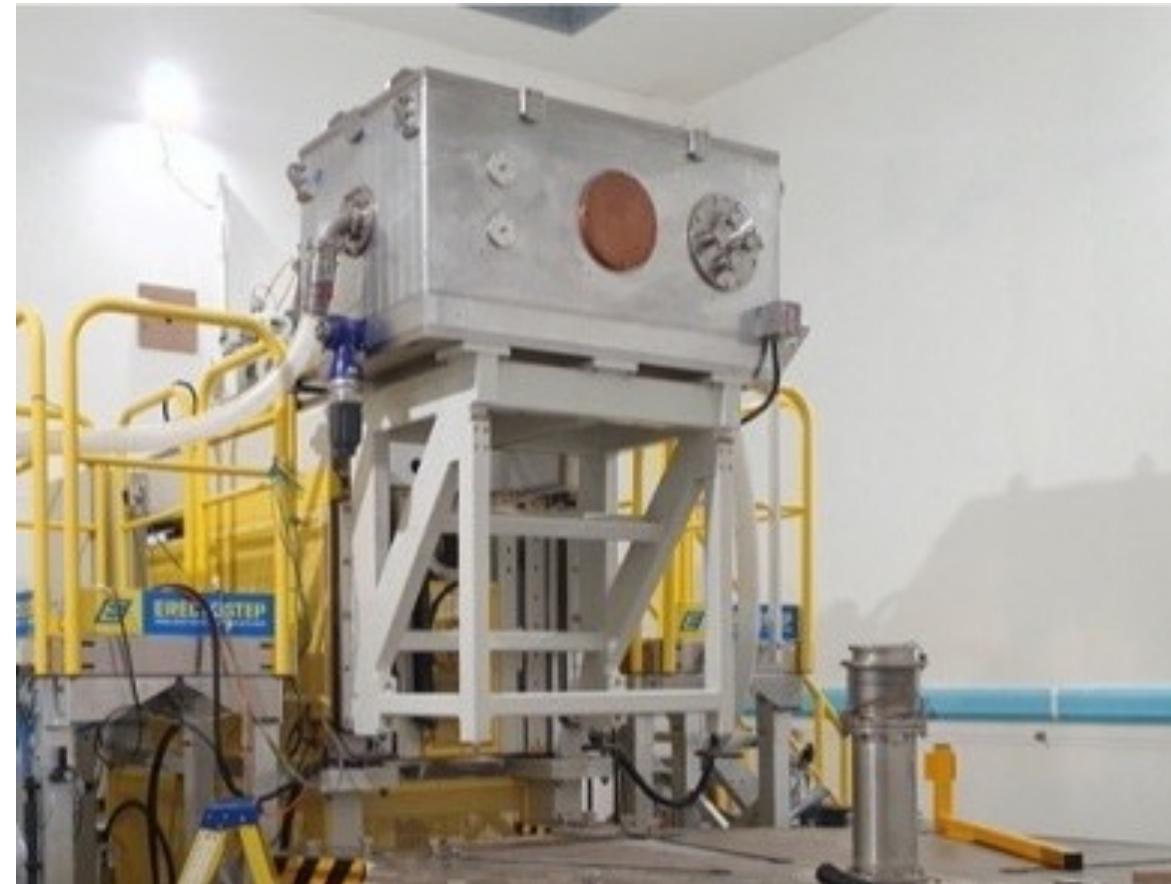
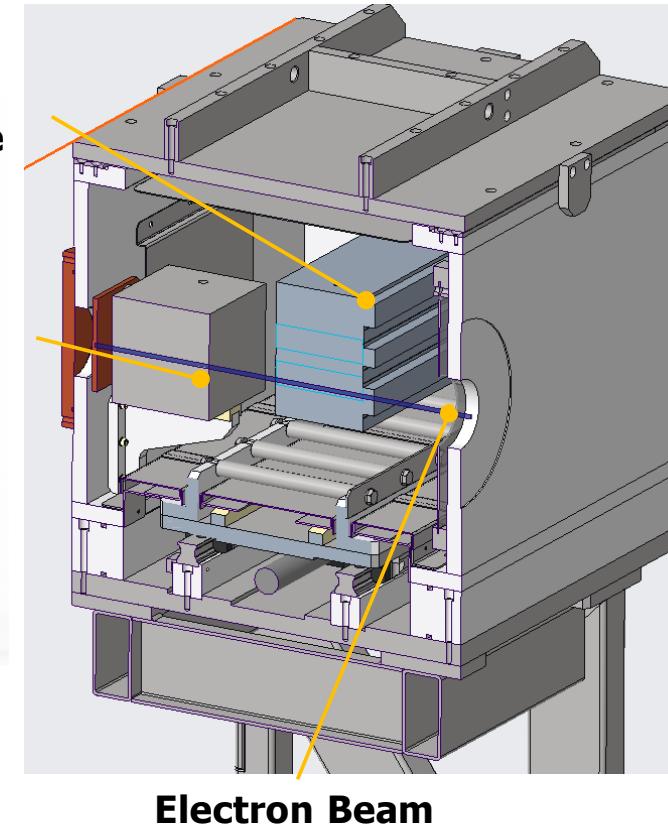
**X-Ray enclosure using augmented reality**



**Completed X-Ray enclosure**

2023

## Machine configuration No 1 of 3: Electron Beam Development



### Vacuum chamber concept

2019

Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.

### Deployment

2023

## Electron Beam Development



**Vacuum chamber sample block  
(0.5mx0.2mx0.2m)**

2019

Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.



**16 Ton of material used**

2023

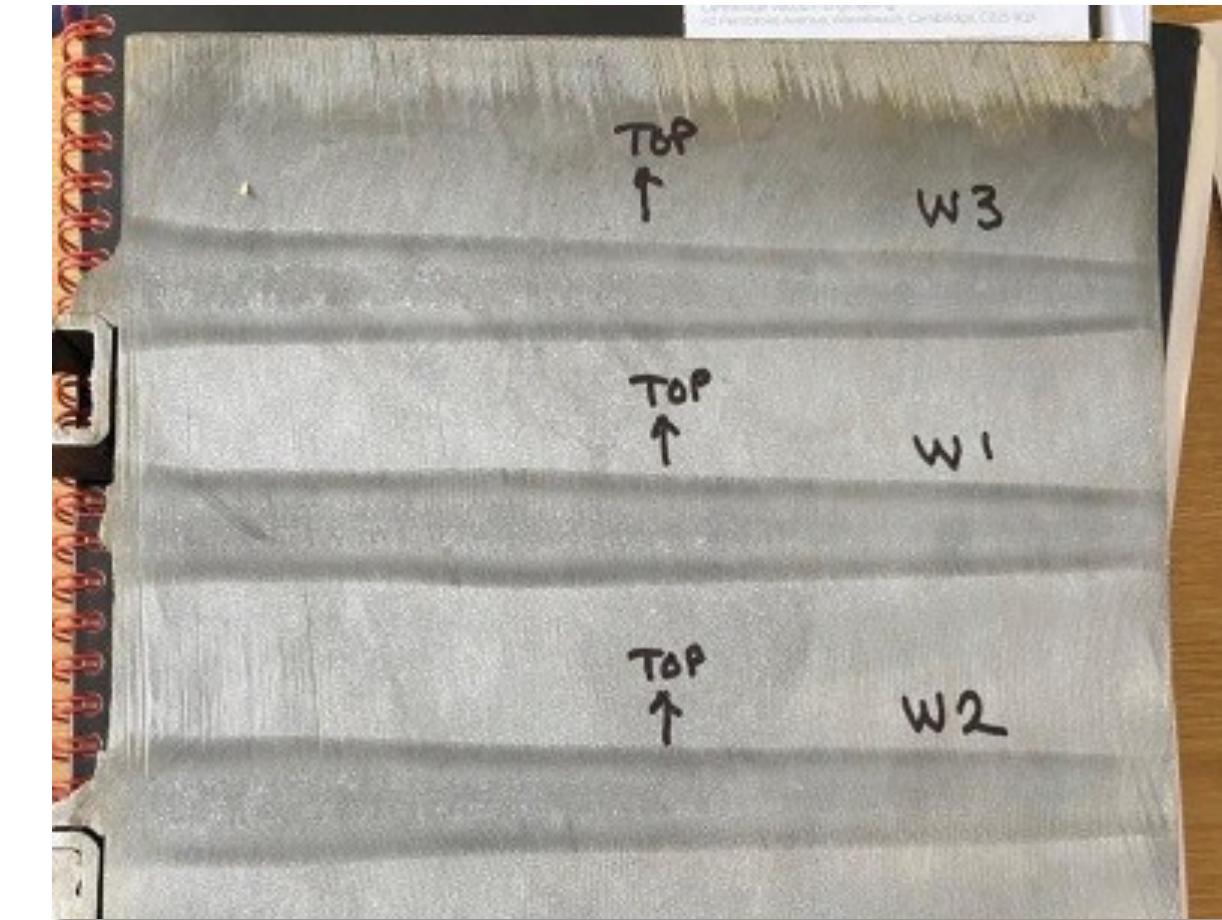
## Electron Beam Development



### Weld Parameter Development

2019

Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.



### Macro Etched Welds

2023

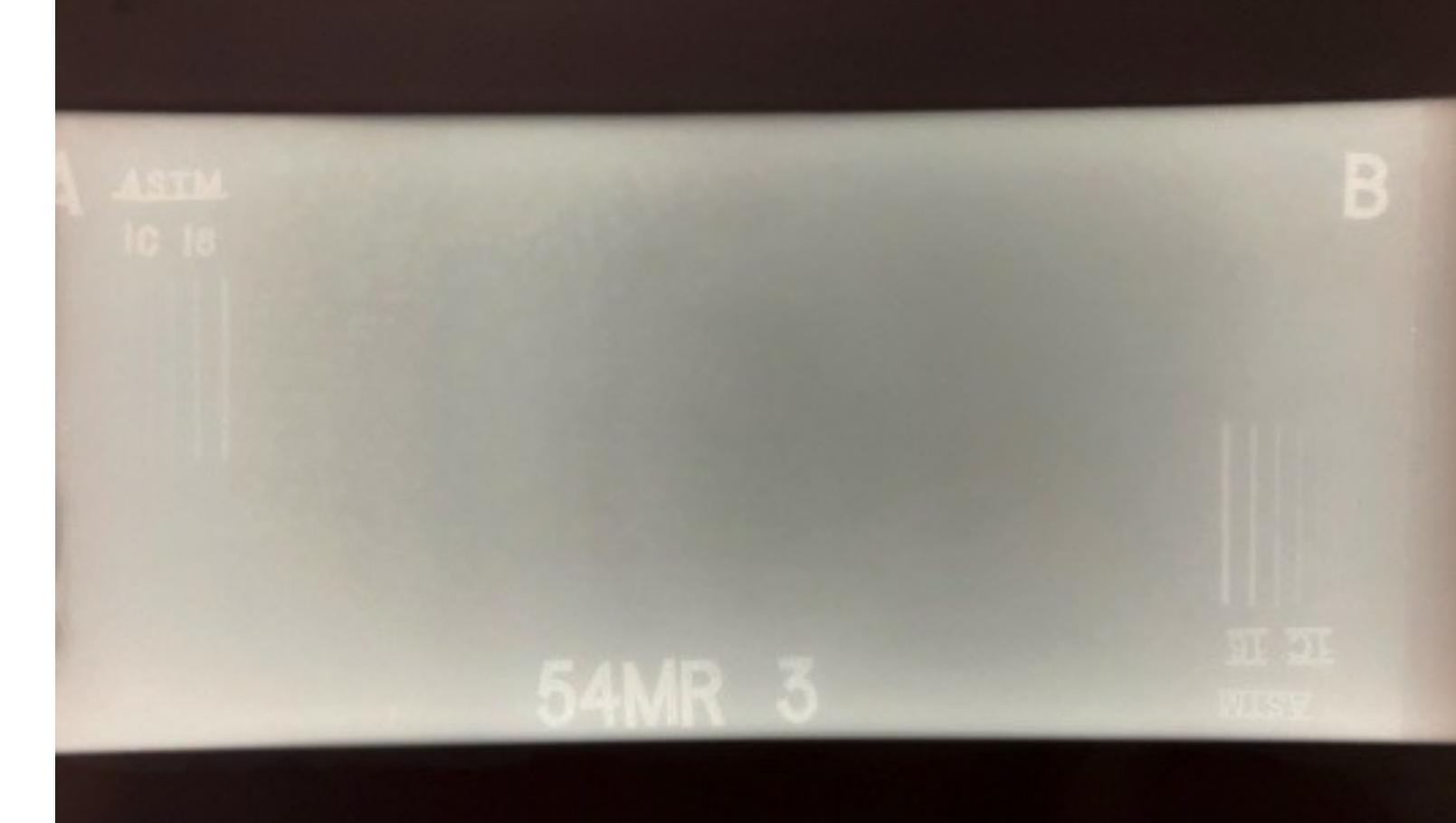
## Electron Beam Development



### Weld Parameter Development

2019

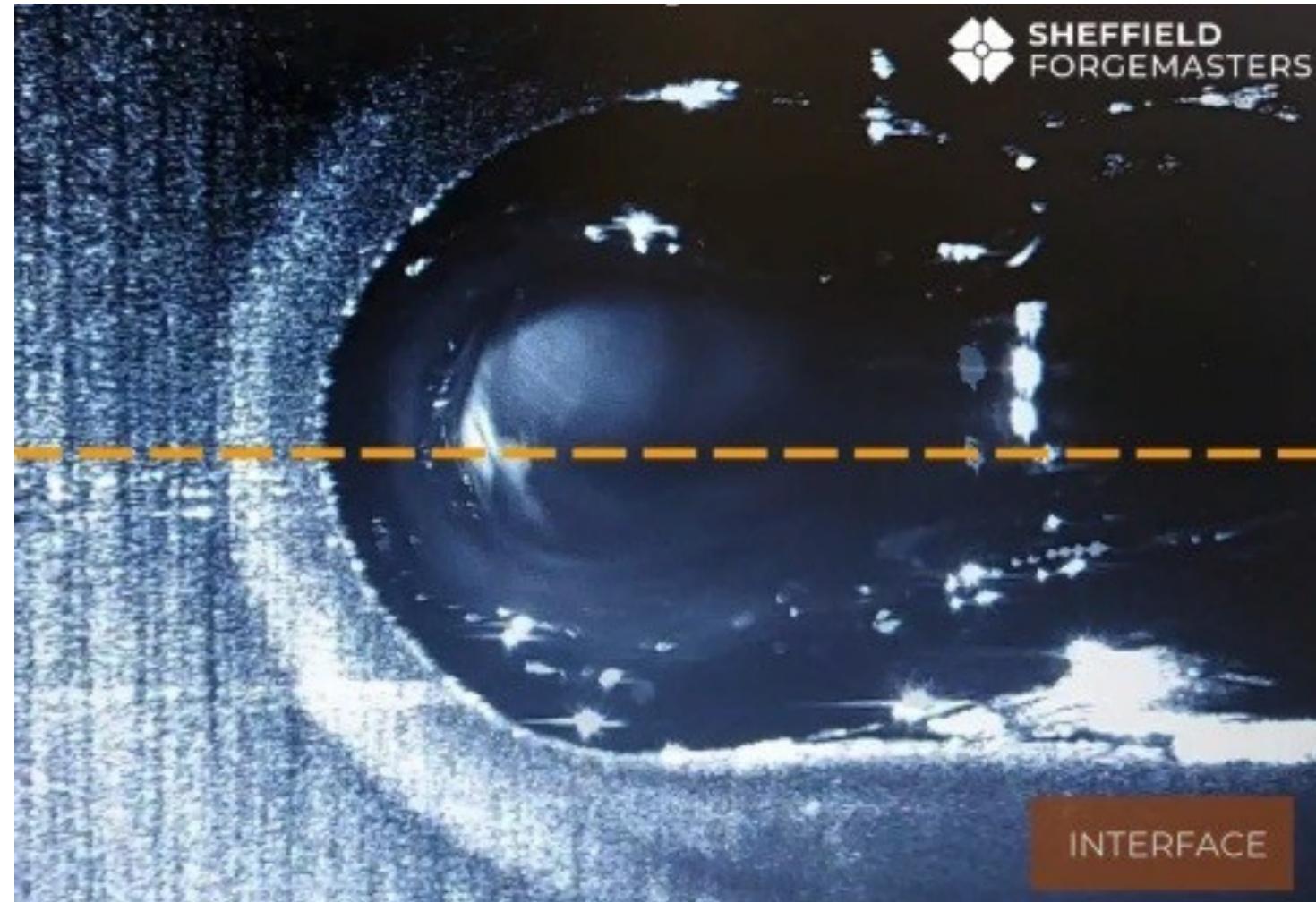
Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.



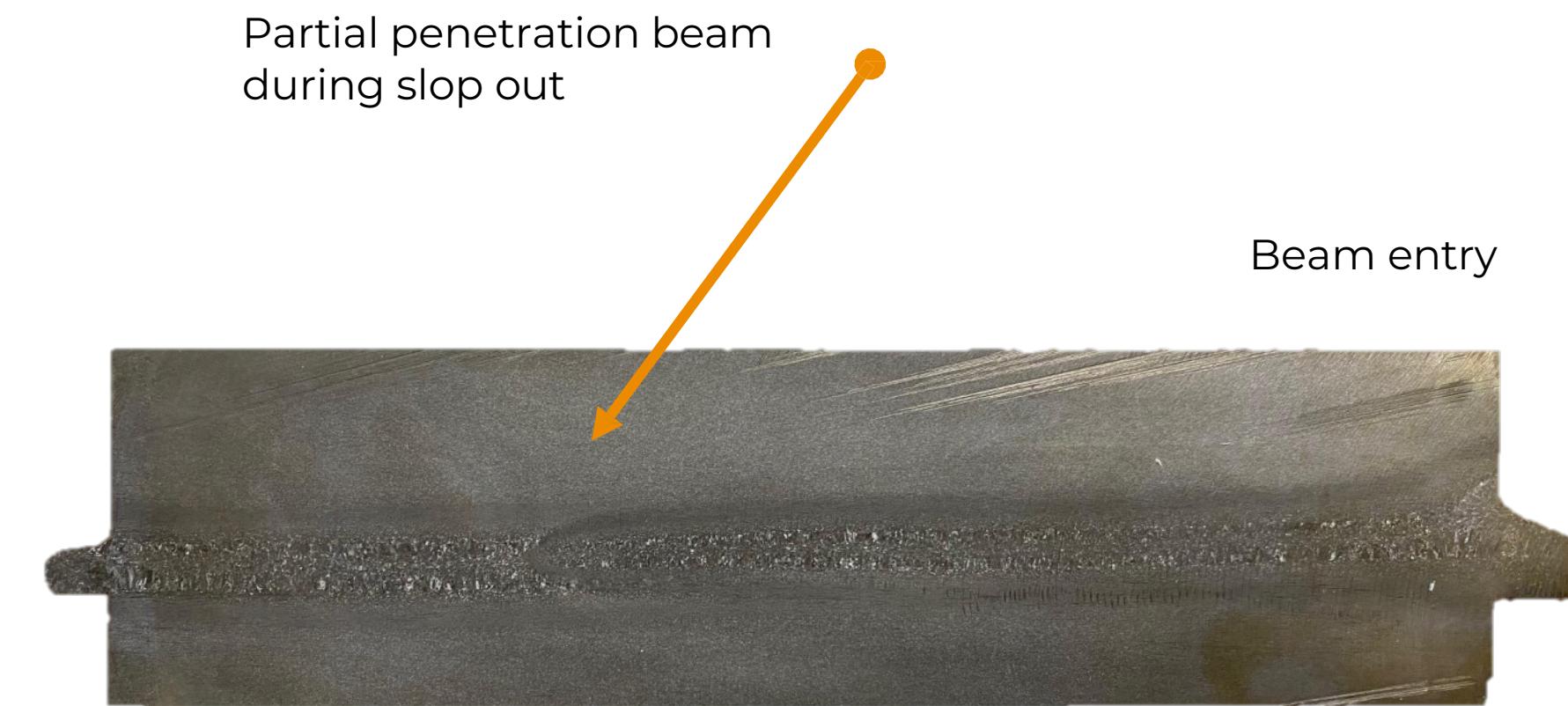
### Macro Etched Welds

2023

## Process Development – Steady State and Slope Out

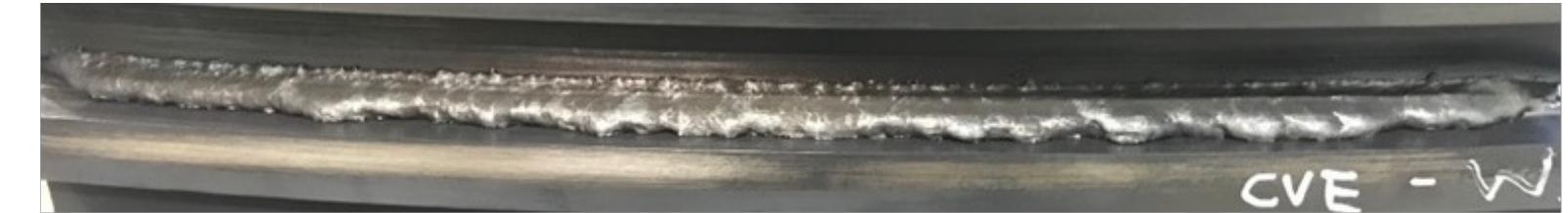


**Keyhole formation during a 200mm weld**

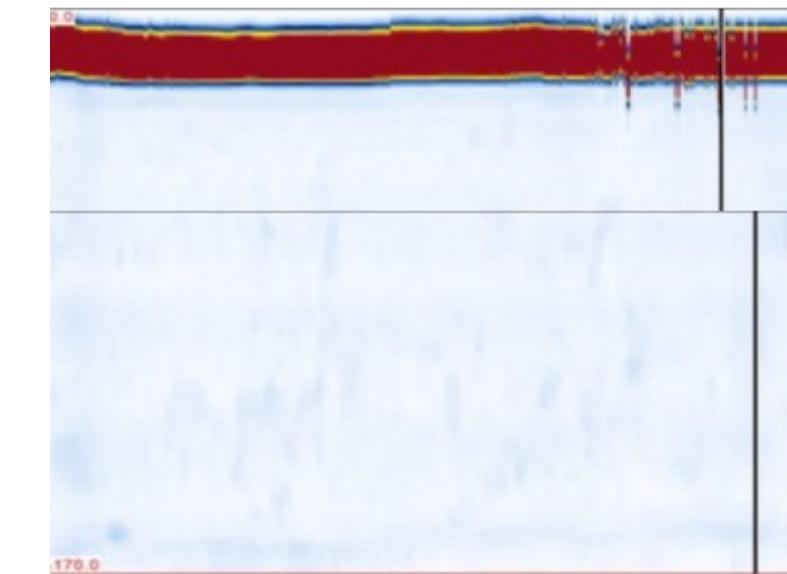


**Slope out development**

## Process Development – Steady State and Slope Out

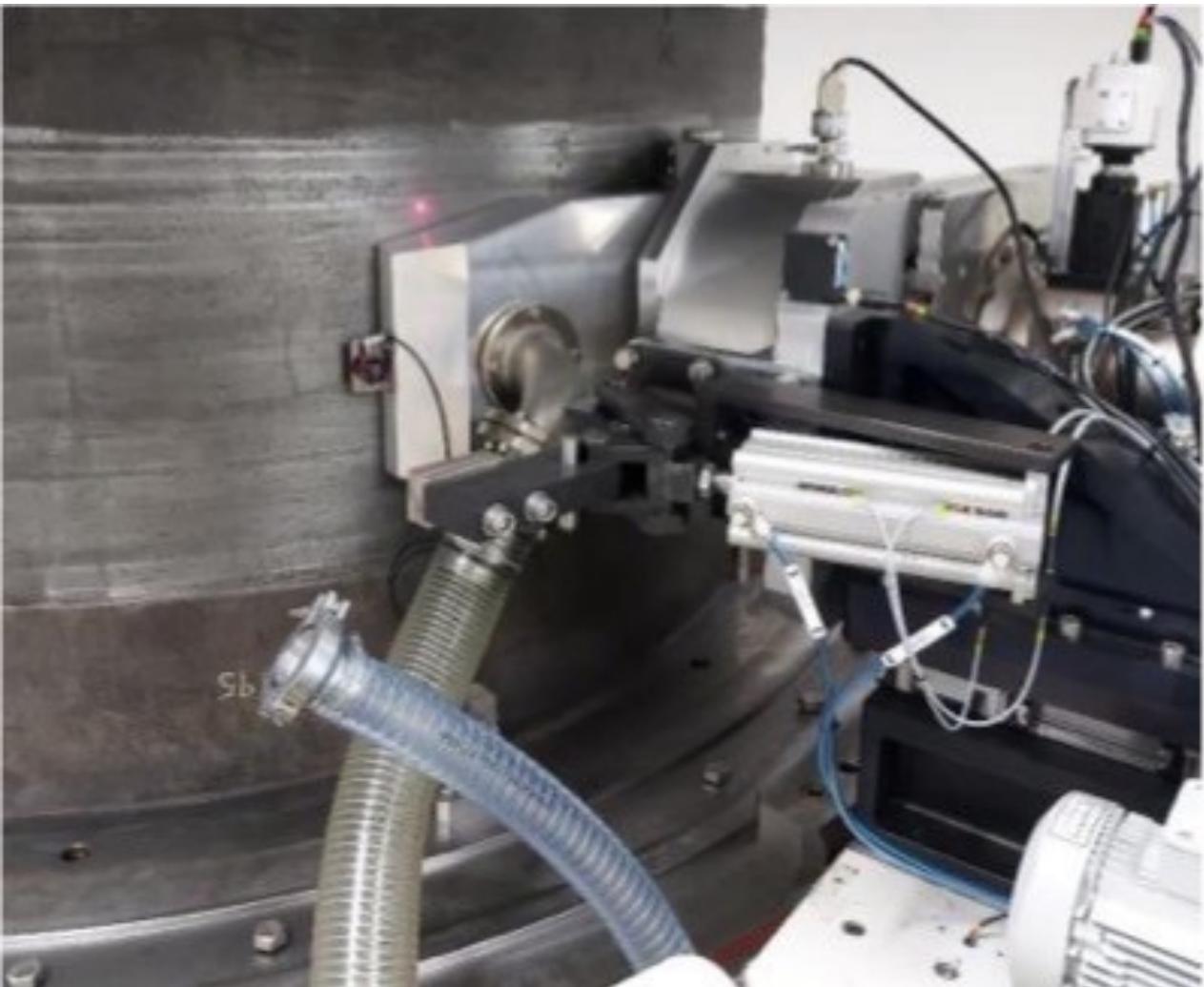


**High Speed Parameters**



**Low Speed Parameters**

Machine configuration No 2 of 3: Vacuum Head for thicknesses less than 80mm.



2019

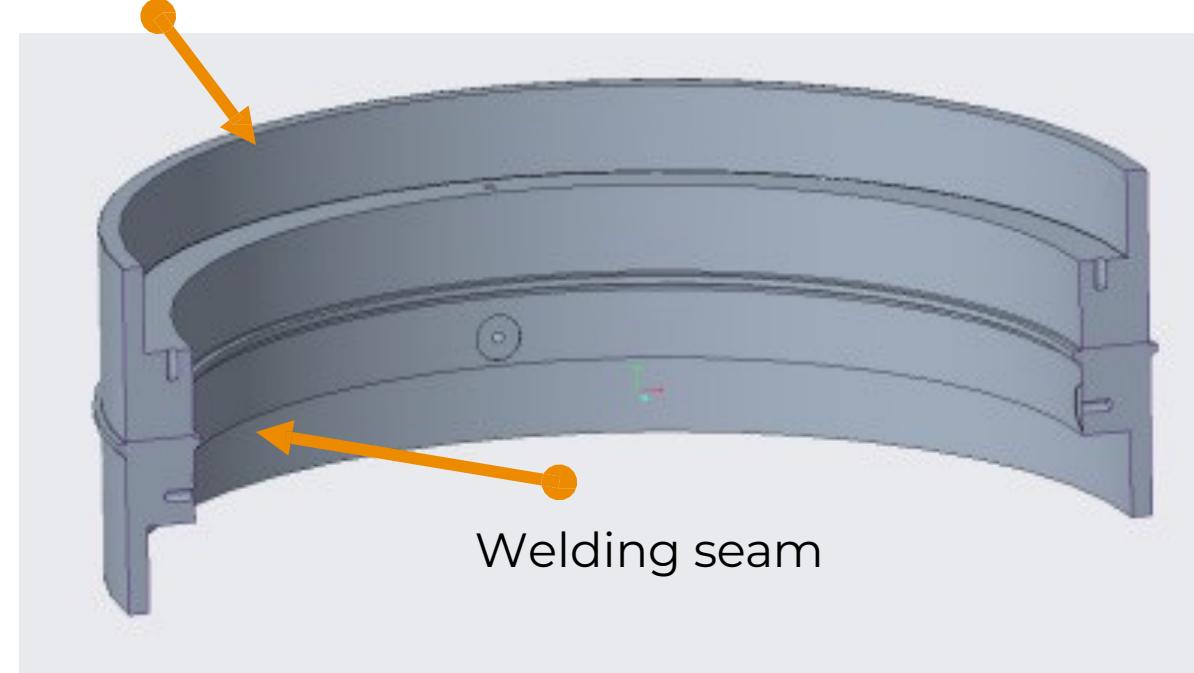
**Sliding Head Welding**

2023

**Sliding Weld on 60mm Cylinder**

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.

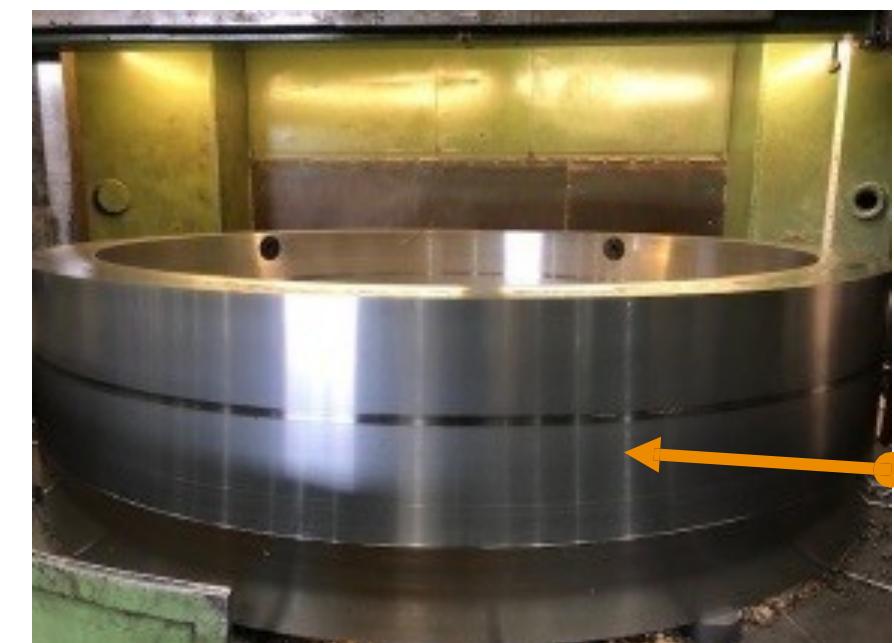
Reduce thickness due  
to weight constrains



**Cross Section of FAT Rings**



**FAT Weld Crown**



**FAT Rings Machining**



2019

3m diameter, 200mm thick factory acceptance testing (FAT) rings



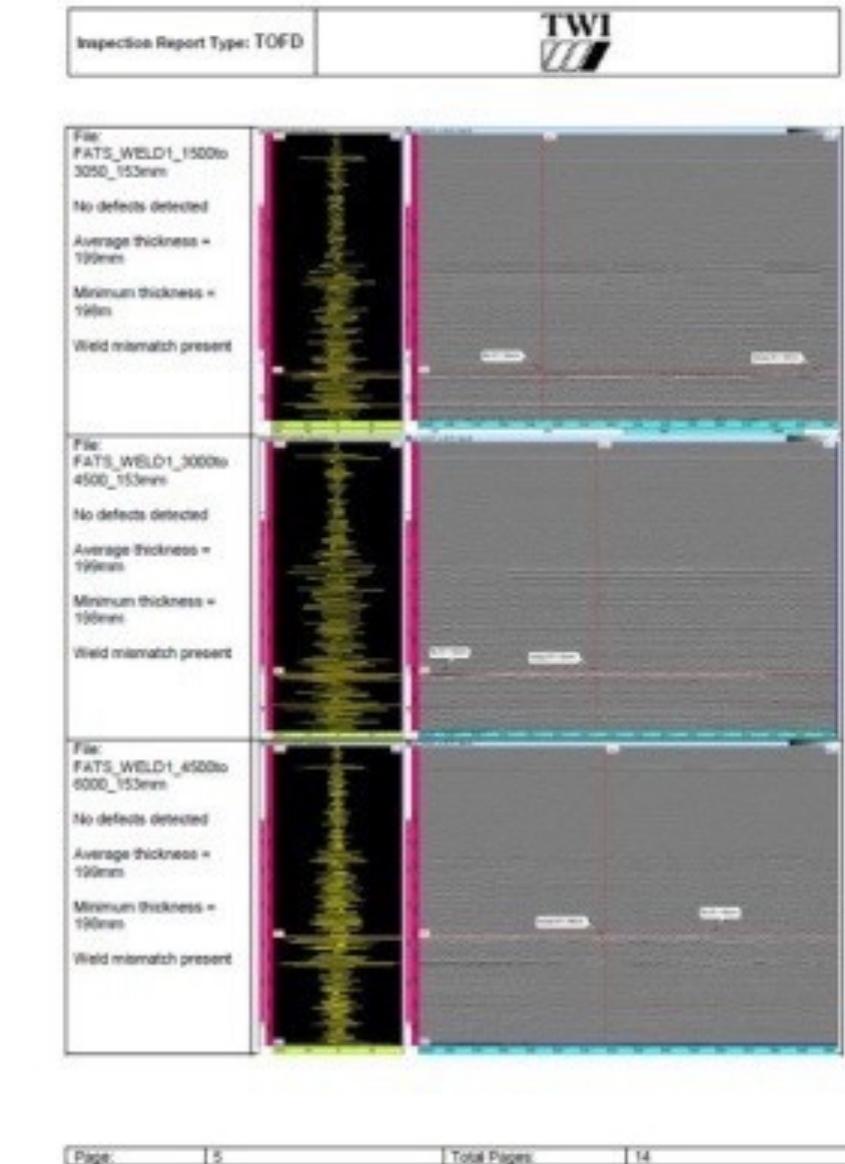
2023

## Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



2019

**FAT Weld Witnessed by ONR & EA**

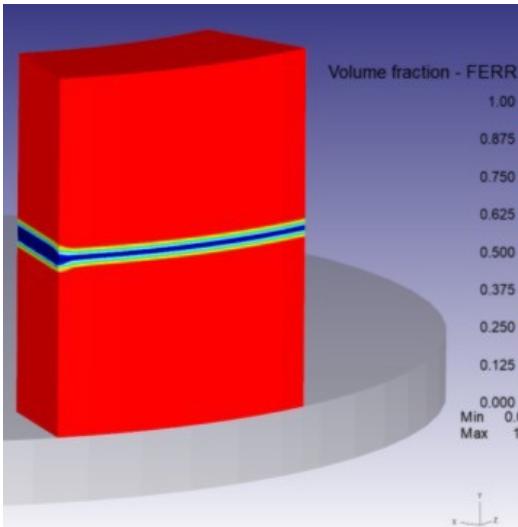
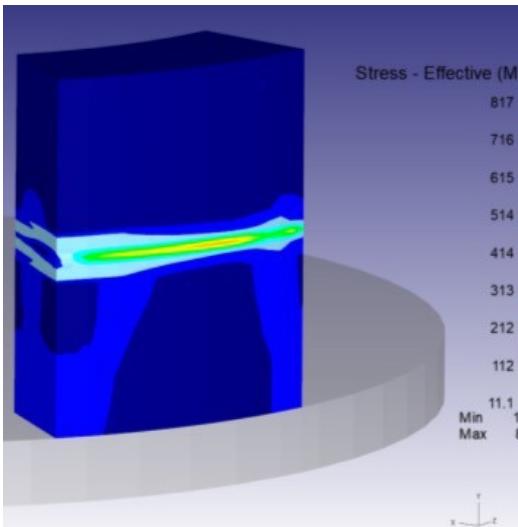


**2023**

**TWI Phased Array UT**

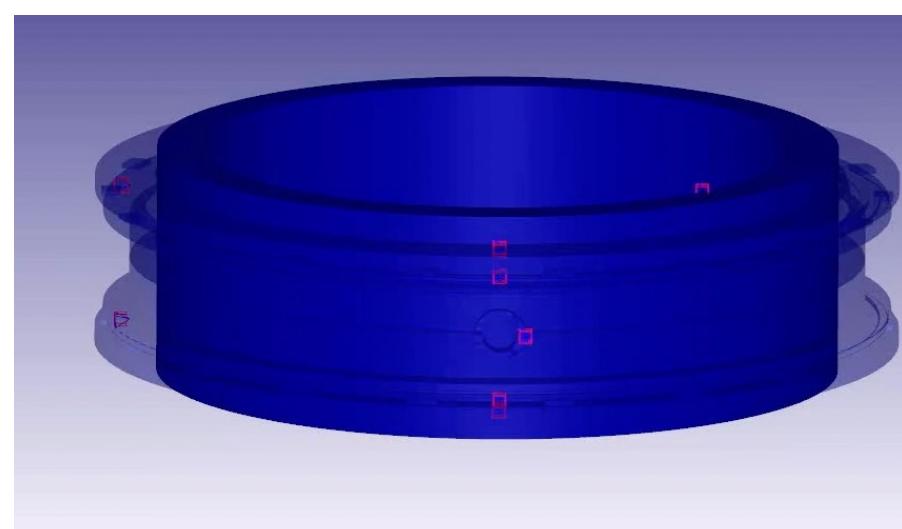
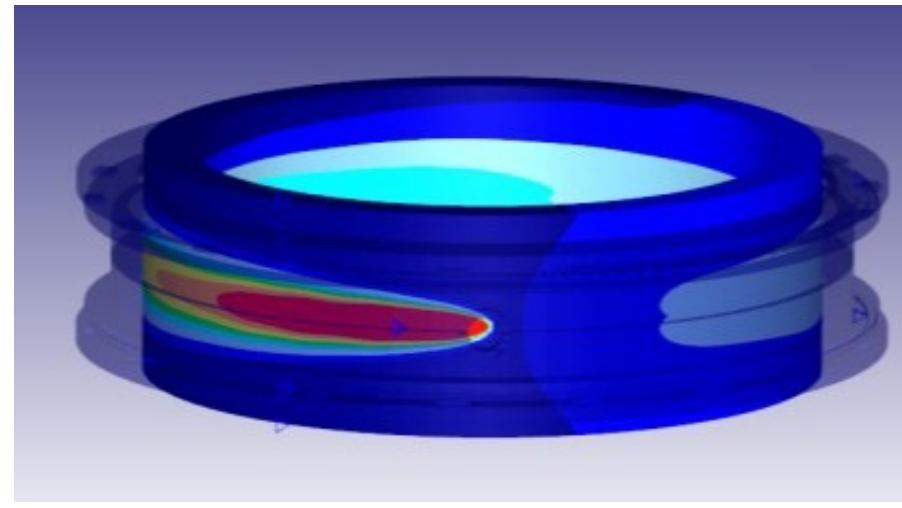
2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.

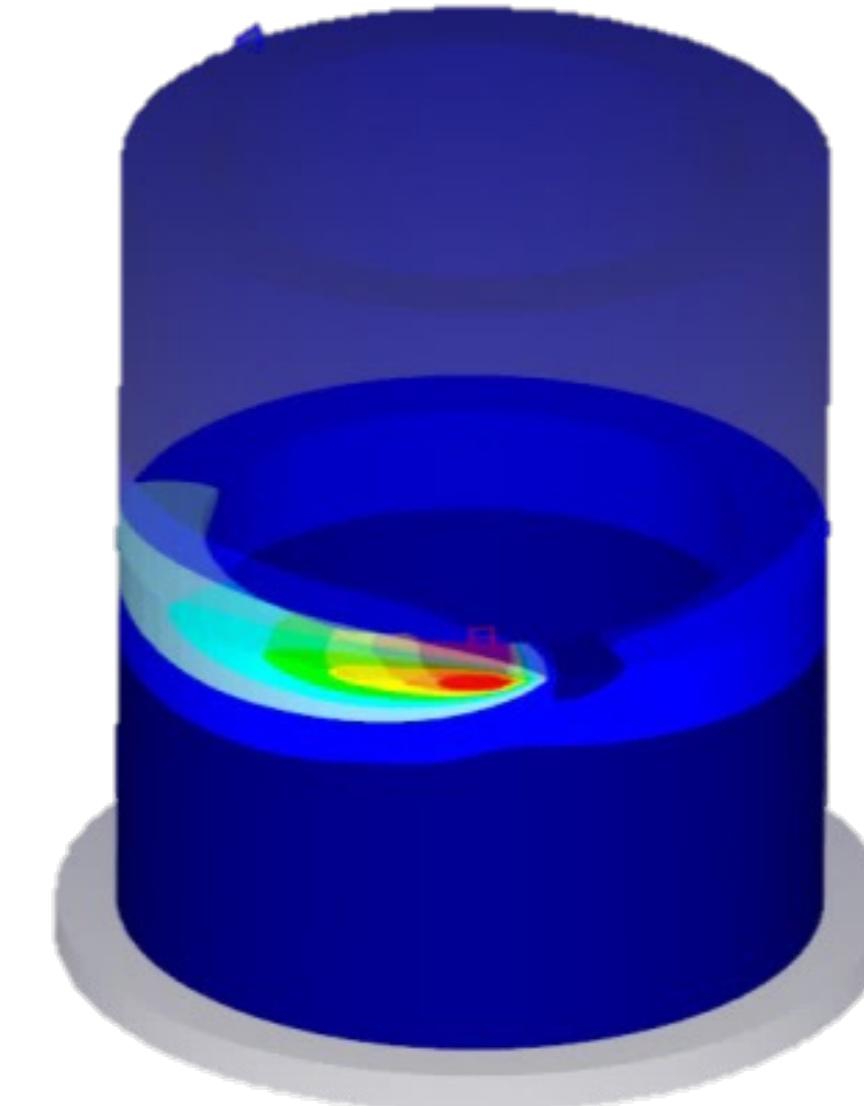


2019

**Residual Stress & Microstructure**



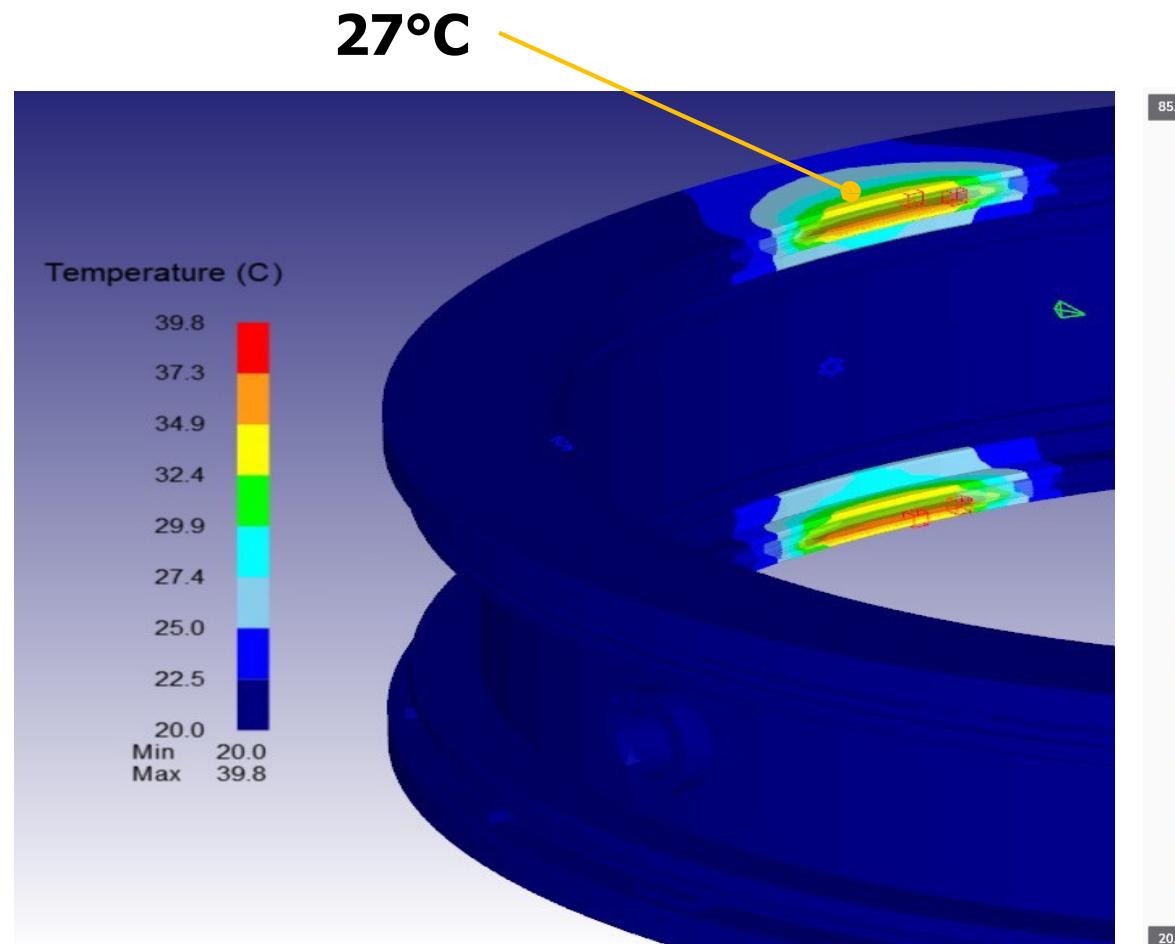
**Tooling Heat Loads**



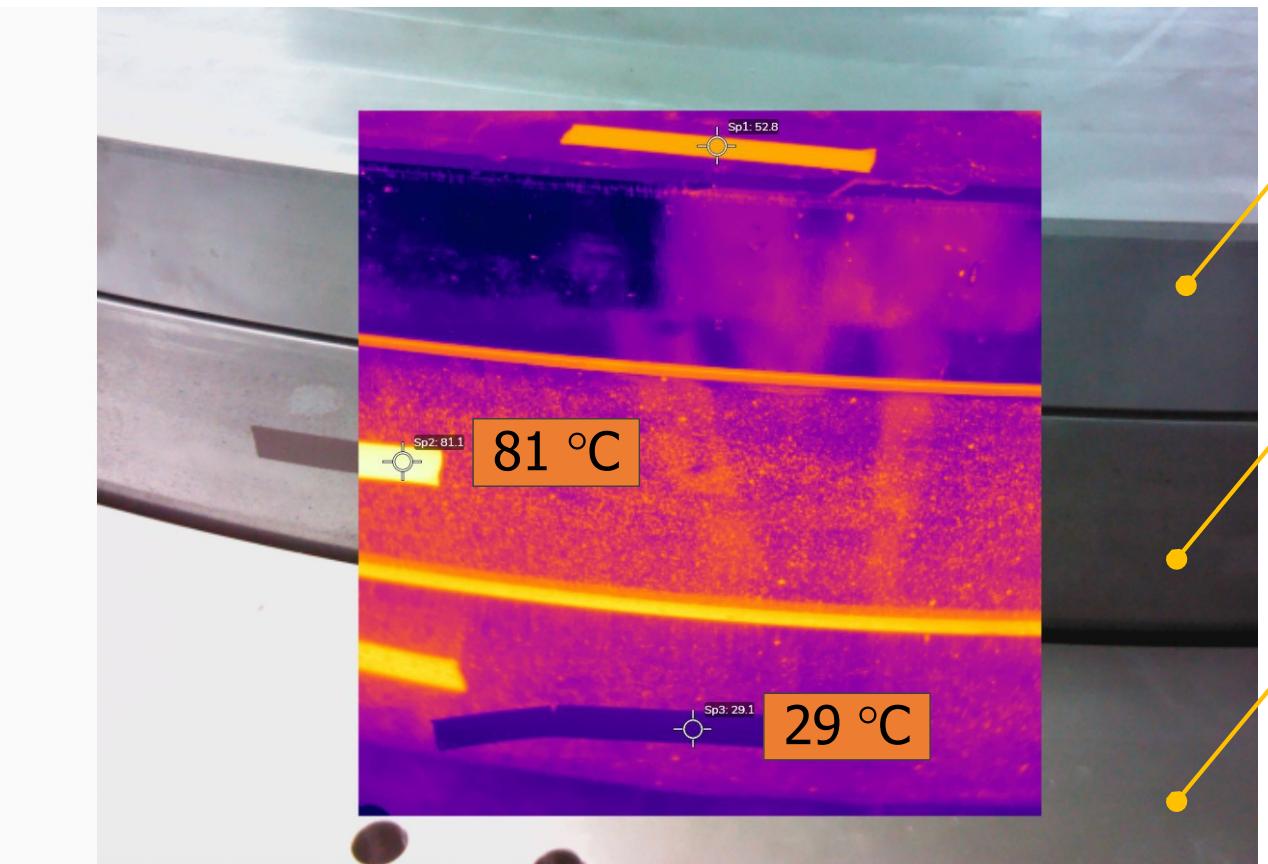
**Vessel Temperature**

2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



**Vacuum Jacket Temperature**

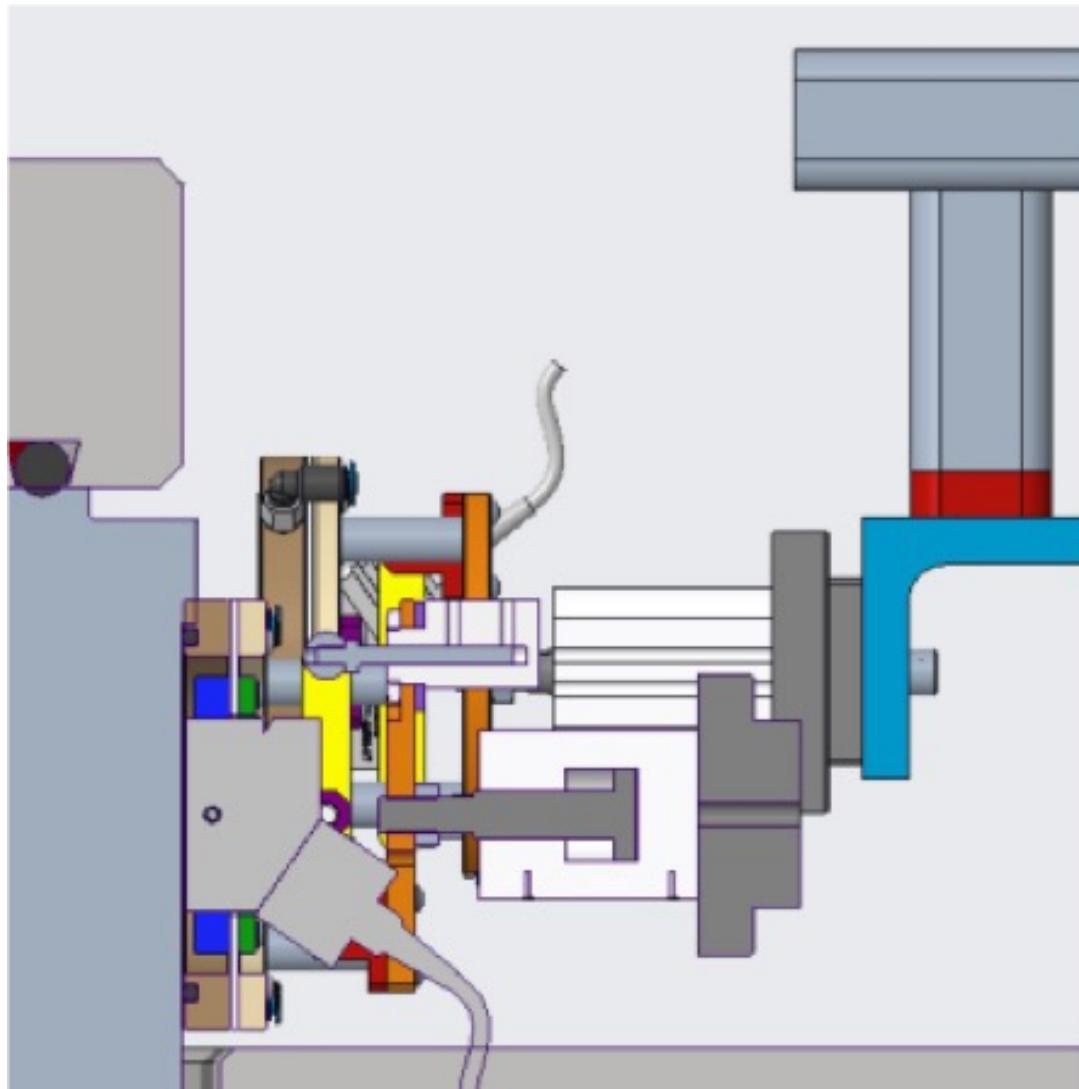


**Surface Temperature After Welding**

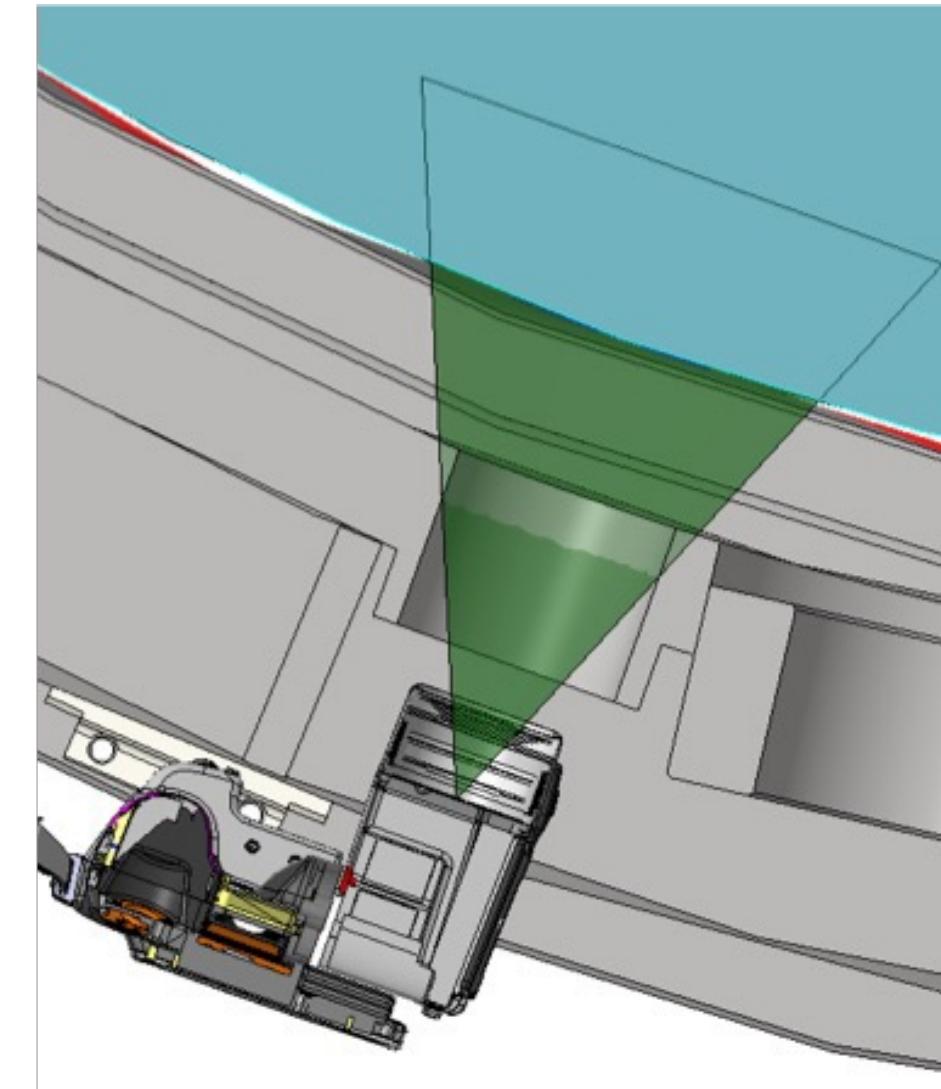
2019

2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



# UT Sensor

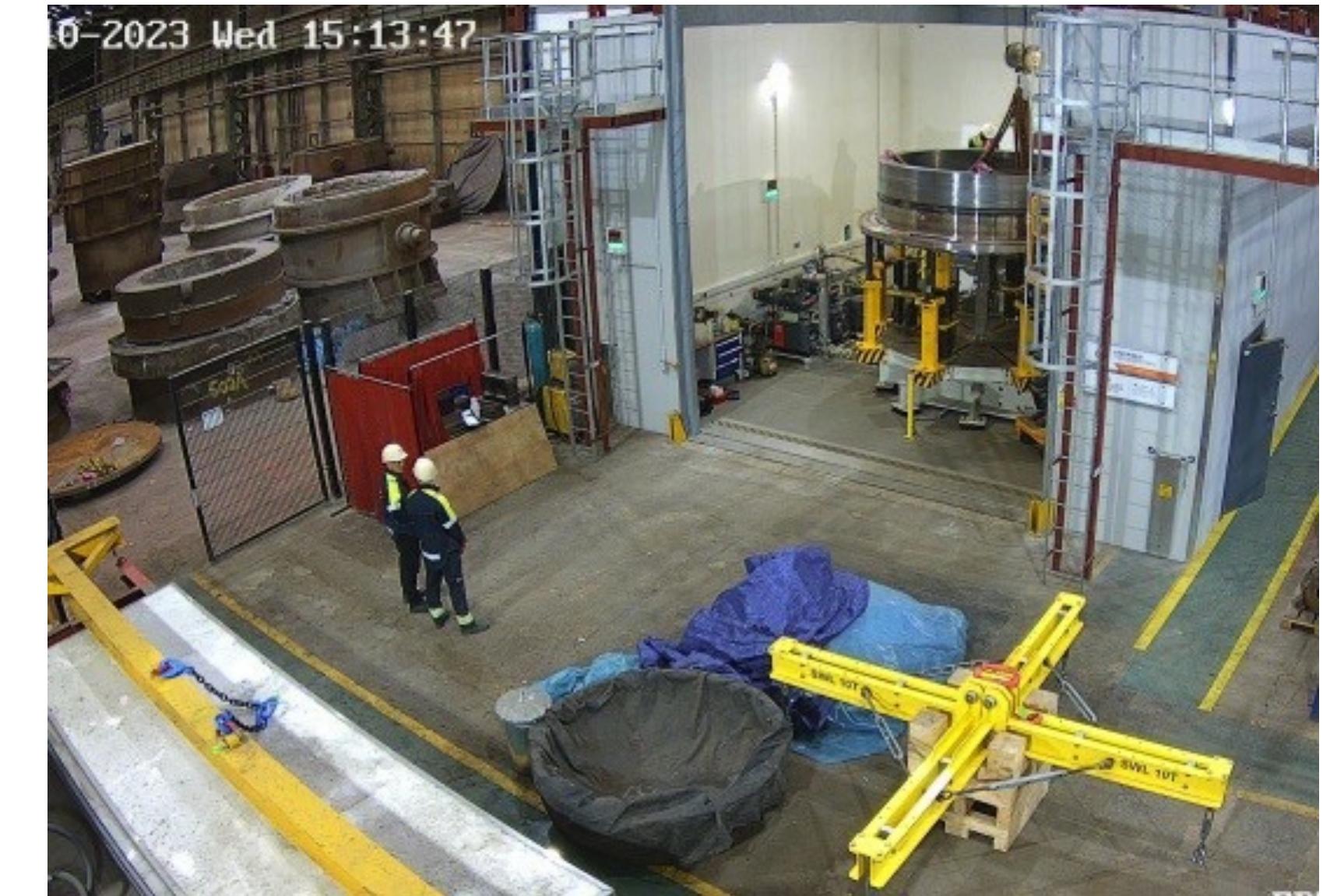


# Temperature Sensors and DIC for stress

2019

2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



2019

3m diameter, 180mm thick site acceptance testing (SAT) rings

2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



2019

First set of 3m diameter, 180mm thick rings to be welded 25<sup>th</sup> October 2023

2023

## Vessel Fabrication Completed



2019

Third parties have independently carried out NDE with no recordable indications.  
All welds passed internal pressure vessel fabrications standards.

2023

**04**

**CONCLUSIONS AND  
FUTURE WORK**



# Advantages of Implementing Electron Beam Welding

## Advanced Manufacturing



**A) Full x-ray enclosure**

Capable of housing 3m dia. x 4.5m, 100 Ton



**B) Local vacuum approach**

Reached under 10min



**C) Worlds first**

3m diameter (200mm thick) weld in just over 2hrs



**D) Weld quality**

Properties similar or better than parent material



**Integrated into the conventional Manufacturing Process at Forgemasters**



**Produces precise and high-quality welds with deep penetration and minimal distortion**



**Narrow Heat-Affected Zone (HAZ) and High Joining Rate**



**Reduced inspection campaign**



**Supply of complete sub assemblies ready for next manufacturing steps thus reducing time and cost**



**Eliminate the use of filler material, welding gases and pre/post heat requirements**

## Advanced Manufacturing

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- “In order to meet the industry/customer demands we need to drive innovation”***
- “Innovation and technology are critical to sustain competitive advantage”***
- “The UK organisations need innovation to compete globally”***
- “Advanced manufacturing methods are critical to reduce manufacturing cost and delivery time, but challenges exist to codes and standards acceptance.”***